The effects of repeated under canopy burning operations in commercial Pine plantations in Mpumalanga, South Africa on fuel loads and stand productivity

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Declaration

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Summary

Wild fires are a risk to commercial forestry companies in South Africa resulting in commercial areas being damaged or destroyed. Viable methods to mitigate this risk in an effective, economical and sustainable manner need to be practised to ensure the sustainability of the forestry industry in South Africa.

Prescribed under canopy burning is a viable option to reduce fire risk and fire damage and is implemented in South Africa. This thesis documents the effects of repeated prescribed under canopy burning operations on fuel load reduction, stand productivity as well as the effect on tree damage.

Three trial sites were selected in Mpumalanga, South Africa; namely Blyde plantation, Berlin plantation and Nelshoogte plantation. Two trial sites consist of three control plots, three twice burnt plots and three plots burnt on three occasions. One trial site (Blyde) consists of three once burnt plots and three plots burnt on three occasions. The trials commenced in 2014 with the third burn treatments being implemented during 2019, and final measurements in 2020.

Burning conditions and fire intensity: Under canopy burning treatments were of a low intensity. Average fire front flame heights were 0.20m and average fire line intensity ranged between 4 kw/m to 11 kw/m. The average surface rate of spread ranged between 0.1m/min and 0.2m/min and the surface fire heat per unit area ranged between 3080 kJ/m^2 and 4089 kJ/m^2. These low intensity burning treatments resulted in minimal tree damage on most plots.

Forest floor mass: Forest floor mass was reduced on all three trial sites. *Pinus patula* trial sites experienced an average reduction of 16.3 t/ha per burning treatment and the *Pinus elliottii* trial site experienced an average reduction of 4.5 t/ha. The total forest floor fuel load reduction in areas that have never received a burning treatment compared to sites that received 3 burning treatments is an average difference of 48.8 t/ha in *Pinus patula* stands. The reduction in the forest floor fuel load for sites that received 1 burning treatment and 3 burning treatments in *Pinus elliottii* stands is 9 t/ha.

The degree of fuel load reduction is statistically significant in *Pinus patula* and *Pinus elliottii* stands.

Tree damage: No tree mortality occurred in the *Pinus elliottii* trial stand, however tree mortality was observed on both the *Pinus patula* trial sites. Tree mortality occurred in unburnt plots, as well as plots that received burning treatments. No correlation between tree mortality and burning treatments could be established. Root damage was observed on all three trial sites. A minor degree of root damage occurred and only one observed tree was found to have root damage in the coarse root class. No crown damage was observed to have occurred directly after burning. Litter fall was observed for 7 months and an increase in litter fall occurred after the burning treatment on the Nelshoogte trial site due to a higher fire intensity on the day of the burn. Average monthly litter fall rates ranged from 1 t/ha to 0.2 t/ha in *Pinus elliottii* with the highest amount of needle drop occurring in the winter months and the least occurring in the spring/summer months. *Pinus patula* sites experienced an average range of needle drop from 1.5 t/ha to 0.3 t/ha with the highest amount of needle drop occurring in the winter months and least occurring in the spring/summer months.

Growth responses: Erratic differences in growth increment were observed, indicating that the impact of the specific site had a significant impact on growth responses. The low intensity burning treatments had an insignificant impact on growth responses on the Blyde site. There was a significant interaction between site and burning treatments among the *Pinus patula* trials. The Nelshoogte site experienced the highest fire intensity during the burning treatment, this site also experienced the highest degree of root damage as well as a decrease in Periodic Annual Increment (PAI) of 4 m^3/ha/a. In contrast, the Berlin experiment showed a significant increase in PAI following repeated burning amounting to 3 m^3/ha/a.

Opsomming

Onbeheerde brande is 'n risiko vir kommersiële bosbouondernemings in Suid-Afrika, wat daartoe lei dat kommersiële gebiede beskadig of vernietig word. Lewensvatbare metodes om hierdie risiko effektief, ekonomies en volhoubaar te verlaag, moet toegepas word om die volhoubaarheid van die bosboubedryf in Suid-Afrika te verseker.

Voorgeskrewe brande onder die kroondak van plantasies is 'n lewensvatbare opsie om brandrisiko en brandskade te verminder en word in Suid-Afrika geïmplementeer. Hierdie tesis dokumenteer die effek van herhaalde voorgeskrewe brande onder die kroondak op die verlaging van die brandstoflading, opstandsproduktiwiteit asook die effek op boomskade.

Drie proefpersele is in Mpumalanga, Suid-Afrika, gekies; naamlik Blyde, Berlin en Nelshoogte plantasies. Die behandelings verskil in die aantal beheerde brande wat onder die kroondak gedoen is. Twee eksperimente bestaan uit drie ongebrande kontrole persele, asook drie persele wat twee maal en drie persele wat drie maal gebrand is. Een eksperiment bestaan uit drie eenmalige gebrande persele en drie persele wat drie keer gebrand is. Die drie eksprimente is in 2014 begin, die derde beheerde brandbehandelings is gedurende 2019 geïmplementeer, en die finale metings is in 2020 gedoen.

<u>Brandtoestande en vuurintensiteit:</u> Beheerde brande onder die kroondak was van lae intensiteit. Die gemiddelde vlamhoogte van die brandfront was 0,20 m en die gemiddelde brandlyn intensiteit het gewissel tussen 4 en 11 kW/m. Die gemiddelde verspreidingstempo het gewissel tussen 0.1 en 0.2 m/min en die oppervlak vuurhitte per eenheidsarea het gewissel tussen 3080 en 4089 kJ/m^2. Hierdie lae intensiteit brandbehandelings het minimale boomskade tot gevolg gehad.

<u>Bosvloermassa:</u> Die bosvloermassa is op al drie proefpersele verlaag deur die beheerde brand. *Pinus patula*-proefpersele het 'n gemiddelde verlaging van 16.3 t/ha per brandbehandeling ervaar en die *Pinus elliottii*-proefperseel het 'n gemiddelde vermindering van 4.5 t / ha ervaar. Die totale verlaging van die brandstofbelasting op

die bosvloer in ongebrande persele vergeleke met plekke wat 3 brandbehandelings ontvang het, is 'n gemiddelde verskil van 48.8 t/ha in *Pinus patula*-opstande. Die finale verskil in brandstoflading tussen een en drie brandebhadelings op die bosvloer in *Pinus elliottii* persele, is 9 t/ha. Die mate van brandstof reduksie is statisties beduidend in beide *Pinus patula* en *Pinus elliottii* opstande.

Boomskade: Geen boomsterftes het voorgekom in die *Pinus elliottii* proef nie. Daar is egter boomsterftes op beide die *Pinus patula* proefpersele waargeneem. Boomsterfte het egter voorgekom in ongebrande behandelings sowel as persele wat brandbehandelings ontvang het. Geen korrelasie tussen boomsterftes en brandbehandelings kon vasgestel word nie. Wortelskade is op al drie proefpersele waargeneem. 'n Geringe mate van wortelskade het oor die algemeen voorgekom en slegs een enkele boom in die waargenome steekproef het wortelskade in die dikste wortelklas gehad. Geen kroonbeskadiging is waargeneem direk na beheerde brande nie. Tempo van naaldeval is vir 7 maande na brand waargeneem. 'n Geringe toename in naaldeval het plaasgevind na die brandbehandeling op die Nelshoogte-proefperseel as gevolg van 'n hoër vuurintensiteit op die dag van die brand. Die gemiddelde maandelikse naaldeval het tussen 0.2 en 1.0 t/ha in *Pinus elliottii*, met die hoogste hoeveelheid in die wintermaande en die minste in die lente / somermaande. *Pinus patula* persele het 'n gemiddelde naaldeval van 0.3 tot 1.5 t/ha ondervind, met die hoogste hoeveelheid naaldeval in die wintermaande en die minste in die lente / somermaande.

Groeireaksie: Wisselvallige reaksie in opstandsgroei is waargeneem, wat daarop dui dat die effek van die vuurintensiteit en die groeiplek 'n beduidende impak op die opstande se groeireaksie gehad het. Die brandbehandelings met lae intensiteit het 'n onbeduidende impak gehad op die periodieke jaarlikse aanwas (PJA) van die *Pinus elliotti* opstand op Blyde plantasie. Daar was 'n beduidende interaksie tussen behandelings en groeiplek onder die *Pinus patula*-eksperimente. Die Nelshoogte eksperiment het die hoogste brandintensiteit ervaar tydens die brandbehandeling; hierdie proef het ook die hoogste mate van wortelskade ervaar, asook 'n afname in PJA van 4 m^3/ha/a. Daarteenoor het die Berlin plantasie eksperiment 'n beduidende toename in PJA getoon van 3 m^3/ha/a na herhaalde beheerde brand.

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List of Abbreviations

SAFCOL	South African Forestry Company Limited
FMC	Fuel moisture content
kW/m	Kilowatt per meter
I	Fire intensity
kJ/kg	Kilojoule per kilogram
kg/m	Kilogramme per square meter
m/s	Meter per second
TPH	Trees per hectare
SPHA	Stems per hectare
FF mass	Forest floor mass
Ha	Hectare
RD	Relative density
DBH	Diameter at breast height
L layer	Litter layer
F&H later	Fermentation and humus layer
Temp	Temperature
ANOVA	Analysis of variance

1. Introduction

Commercial pine plantations in South Africa are exposed to risks, of which fire can be considered as a prominent risk that needs to be managed. One of the most important factors affecting forest fires is fuel load as it affects the rate of spread and intensity of the fires. In commercial pine plantations, combustible material in the form of branches, litter and undergrowth accumulate and this is known as the fuel load. This fuel load can be a serious fire hazard, however most of it can be removed by burning it under controlled conditions during prescribed burning operations (Evans & Turnbull, 2004).

Prescribed burning can be defined as a science and an art requiring a background in weather, fire behaviour, fuels and plant ecology along with the courage to conduct burns, good judgement, and experience to integrate all aspects of weather and fire behaviour to achieve planned objectives safely and effectively (de Ronde, et al, 2004).

Prescribed under canopy burning is an effective tool that can be used to control fuel loads in commercial pine plantations throughout South Africa. The control of these fuel loads takes place with the effective burning of the surface fuels, including part of the forest floor material under controlled conditions. This results in the reduction of available surface fuels to burn in the event of an uncontrolled wildfire (Teie, 2005), 2005).

Three plantations have been identified where previous research has been carried out. These plantations are Berlin which is situated near Kaapsehoop, Nelshoogte which is situated between Barberton and Badplaas and Blyde which is situated near Graskop. The trial plots in the three plantations all occur in pine plantations and a number of plots have been selected in each compartment to ensure a sufficient amount of replications are available.

1.1 Forestry fires in South Africa

The occurrence of plantation fires within the South African forestry industry is becoming more common. According to de Ronde et al., (2004) many African countries are experiencing serious fire problems. The increasing frequency and intensity of fires are having a negative effect on ecosystems and are leading to a general degradation of the land.

There is a need for forestry companies to mitigate the risks of fire in plantation areas. Historical data from 1980 – 2018 shows that forest fires in South Africa occur every year and range from 5 223 hectares lost in 1985 to over 70 000 hectares lost in 2007. Historical data shows a consistent increase in area lost over the last 4 decades.

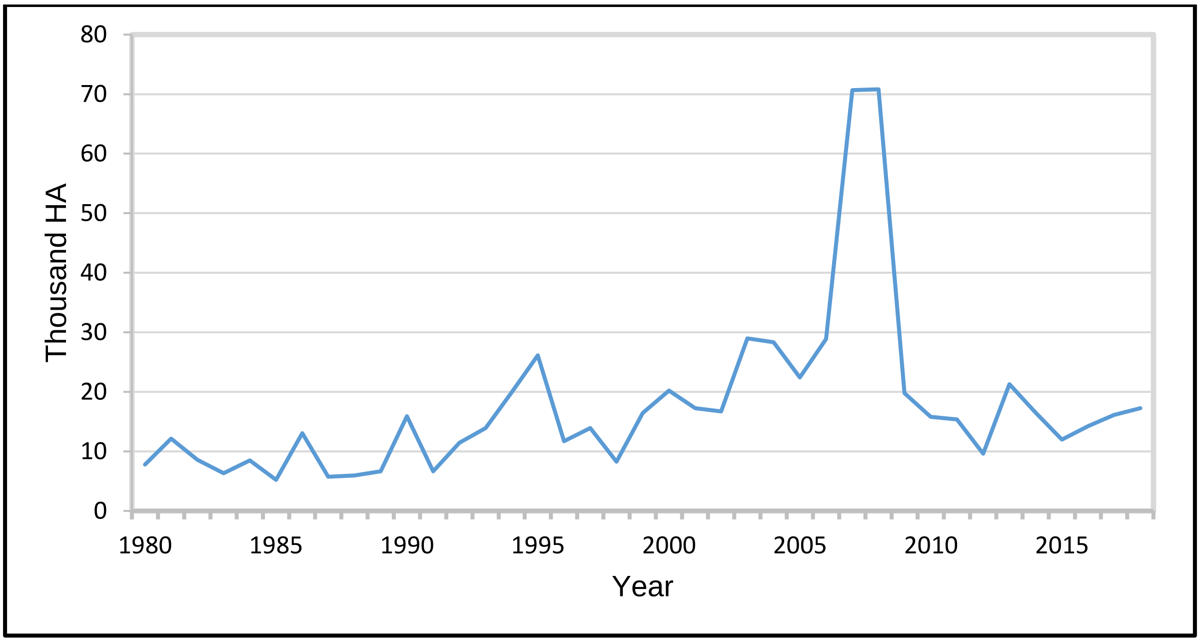


Figure 1.1: Forestry area burnt in South African plantations.

1.2 Problem statement and objective

The South African Forest industry experience fires on an annual basis, which result in substantial damage to plantation areas. With the ever increasing challenge of climate change, weather patterns are becoming more unpredictable, conditions are becoming hotter and drier and this results in increased intensity and frequency of forest fires.

Prescribed under canopy burning operations is an effective management tool that when used correctly will result in the reduction of fuel loads in commercial pine plantations. The South African Forestry Company (SAFCOL) (PTY) LTD has been carrying out prescribed burning operations and positive results have been experienced. This study will assist commercial forestry plantation companies as well as small growers to make informed decisions regarding prescribed under canopy burns. The study will provide information relating to the effects of prescribed under canopy burning on tree growth over a six year period as well the effects of prescribed under canopy burning on tree damage and survival over a six year period.

1.3 Research questions

To investigate the long term effect of repeated prescribed under canopy burning on tree growth, survival and tree damage. Does under canopy burning operations result in a significant fuel load reduction to create fixed defences within the plantation to assist with fire protection?

a. What is the impact of burning conditions on fire intensity?
b. What the impact is of repeated under canopy burning on fuel loads?
c. What the impact is of repeated under canopy burning on tree growth, survival and tree volume growth?
d. What is the impact of fire intensity on crown scorch and root damage?
e. What is the impact of fire intensity on needle drop? Do areas that experience increased fire intensities result in increased needle drop following burning?

Previous research has taken place and some of the publications include: (1) - The effects of fire on tree growth (Scholes & Bird, 2005) (2) - The impact of repeated prescribed burning in semi-mature pine plantation forests of Mpumalanga on fuel loads, nutrient pools and stand productivity (Gresse L. C, 2015), (3) – Analysis of the prescribed burning practice in the pine forest of north-western Portugal (Fernandes & Bothelo, 2003). Other studies have taken place such as (4) – Ecology and management of forest soils (Fisher & Binkley, 2000).

These studies focus on the effect of burning operations on tree growth and tree damage and will focus on results over a relatively short period of time up to 3 years, however continuation of the 2014/2015 research conducted by Gresse, LC will provide data over a period of 6 years.

1.4 Limitations of this study

Weather conditions were a limitation as burning operations could only take place after a specific amount of rainfall had been received. Weather conditions on the day of the burn had to be suitable to attempt a burning operation.

Burning of the trial plots proved challenging as the plots are situated on different plantations, in different geographical areas. The burning of the trial plots provided further challenges as when a suitable day was selected to travel to a plantation to carry out a burn it was found that the area could not burn. This was due to fuel moisture levels not suitable to allow the burn to continue. This challenge was specifically for the Berlin and Nelshoogte trial plots whereby the species is *Pinus patula* and the compacted nature of the litter layer required sufficient drying before any burn could commence. In some instances manual manipulation of the L layer was required to allow aeration for a successful burn.

Initially, the location of the trial plots proved challenging as the trial first took place in 2014 and was now commencing again from 2018. The markings on the trees in each plot had faded and were not visible. However after carefully inspecting the trial plots, it was possible to locate the plots and the trees per plot. The plots were pegged for identification purposes with a label on each peg and each tree was renumbered.

Disturbance of the plots was another challenge as the pegs that demarcated the plots in some instances would go missing or the labels on the pegs would go missing. This could be attributed to animal disturbance, namely; baboons.

Available time was a limitation as the study took place part time over a two year period while other work commitments had to be adhered to.

Despite the above limitations all the trial plots were burnt as required for the study and meaningful data was collected. This data includes growth responses, tree damage, fuel load measurements, litter fall rates and fire intensity of burning operations. Therefore conclusions could be made regarding the suitability and sustainability of prescribed under canopy burning operations in commercial pine plantations.

1.5 Thesis structure

The thesis consists of seven chapters. The introduction is followed by a literature review relating to the subject. In Chapter 3 the methodology is discussed in detail, including all materials used as well as methodology to collect data. The results of the study are discussed in Chapter 4 having been obtained through analysis of the data. Chapter 5 is the discussion of the results and explanation of the outcomes of the study in comparison with other similar studies. A conclusion follows Chapter 5 and Chapter 7 contains the main recommendations that can be implemented as a result of the study.

2. Literature Review

2.1 Prescribed under canopy burning

Fire is a threat to plantation forests and forest fire planning is needed to protect plantations and to mitigate this risk. In protecting any plantation, the aims are to (1) prevent outside fires spreading in, (2) prevent fires being ignited inside; and (3) limit the spread of a fire. Fire protection strategies require fixed defences as one of the fire protection tools (Evans & Turnbull, 2004).

The reduction of combustible material on the forest floor is a fixed defence. In older plantations, branches, litter and undergrowth accumulate and is known as the fuel load and can be a serious fire hazard. Most of this material can be removed by burning it under controlled conditions. This practice is known as prescribed burning (Evans & Turnbull, 2004).

2.2 Burning conditions

Prescribed under canopy burning takes place during the wet season. The aim of prescribed under canopy burning is for burning to take place under specific conditions to allow for a cool, low intensity fire to burn the top layer of fuel which dries out, however the lower layers of fuel are too wet to burn. This type of burning operation prevents damage to soil and trees (Gresse, 2015).

2.2.1 Wind

Wind is the most dynamic variable influencing fire behaviour. Wind provides oxygen to the fire and affects the rate at which fuels dry ahead of the fire front (Trollope et al., 2004). Wind affects fire behaviour in that it affects fire intensity and rate of spread of the fire. Wind directs the flames at an angle which increases the rate of drying for the fuels ahead of the flame. This results in an increased rate of spread and higher intensity fires. The direction of the wind will affect the direction of the spread of the fire (Teie, 2005).

Wind is a critical weather condition that needs to be considered before prescribed under canopy burning can take place. The combustion rate of fire is positively influenced by the rate of oxygen supply to the fire, thus influencing fire behaviour (Trollope et al., 2004).

2.2.2 Air Temperature

As air temperature increases fuel moisture decreases and this has a direct impact on the intensity of the fire during a prescribed burning operation (Trollope et al., 2004). Air temperature is usually at its highest during 12H00 and 15H00, and during this period the air moisture content and the fuel moisture content is the lowest. Air temperature decreases at night and this cool air results in a higher fuel moisture content. During this time fires can more easily be brought under control (Trollope et al., 2004).

2.2.3 Relative humidity

Relative humidity (RH) can be defined as the ratio between the amount of water vapour a unit of air contains at a given temperature, and the maximum amount of water vapour the unit of air can contain at the same temperature and pressure (Trollope et al., 2004). RH influences the intensity of fires, as it has an effect on the fuel moisture content of the fuels.

As the RH increases, so too does the fuel moisture increase, and as the RH decreases, the moisture content of the fuel decreases. On days when the RH is low, the air is dry and the fuels will dry resulting in more intense fires. To ensure a cool prescribed burn the RH on day of burn should be a minimum of 25% (Teie, 2005) and according to SAFCOL, the requirements for carrying out a prescribed under canopy burn require that the RH should be between 25% and 50% on the day of burn (SAFCOL, 2018).

2.2.4 Fuel Moisture

Fuel moisture content (FMC) is the amount of water in the fuels. Fuel moisture is obtained from the atmosphere, precipitation and the ground (Trollope et al., 2004). The fuel moisture content of fuels will affect the fire intensity and rate of spread. Drier fuels will burn more readily, resulting in more intense fires. The opposite is true for moist fuels (Teie, 2005).

Different types of fuels have different degrees of fuel moisture content. Fine fuels are the fuels in which the fuel moisture content can change the quickest. The fine fuels are the carriers of the wildfires. Live fuels have very high moisture content however can burn and are consumed by fire when there is enough dead, dry fuel to support combustion (Teie, 2005).

2.3 Fuels

Different types, amounts and condition of fuels exist in different environments. Fuels vary in type such as grasses, brush, timber and slash as well as in amount measured in tons per hectare and in condition as the fuel can be completely saturated or completely dry. These factors affecting fuels will affect fire behaviour. Fuels can be divided into three groups, namely; ground fuels, surface fuels and aerial fuels (Teie, 2005).

The two main fuel sizes are fine fuels and coarse fuels. Fine fuels are made up of grasses, small branches, pine needles and leaves with a diameter of up to 6 mm. They dry quickly and need little heat to ignite. Fine fuels can burn very quickly if well aerated or very slowly if they are compacted. Coarse fuels are made up of thicker branches, logs and stumps. Coarse fuels dry more slowly and require more heat to ignite however when burning will continue to burn for extended periods of time (Trollope et al., 2004).

2.3.1 Ground Fuels

Ground fuels include all combustible material below the loose surface litter and consist of decomposed plant material (Trollope et al., 2004). Ground fuels are made up of the deep litter layer, roots and rotten buried logs beneath the ground surface (Teie, 2005).

Ground fuels generally burn with low intensity and therefore do not play a major role in fire behaviour. Roots can carry fires underground spreading into unburnt areas and ground fuels can smoulder for a long time undetected (Teie, 2005).

2.3.2 Surface Fuels

Surface fuels include loose surface litter such as fallen leaves, twigs and bark. These fuels are characterised as fine fuels and can support intense surface fires (Trollope et al., 2004). Surface fuels can go up to two meters in height and are the fuels in which fires usually start (Teie, 2005).

Surface fuels are responsible for most fires spreading and for carrying the fires to the aerial fuels. Due to the fact that surface fuels are usually fine fuels the rate of drying is quick and fuel moisture content is most drastically affected in surface fuels, leading to higher rates of spread (Teie, 2005).

2.3.3 Aerial Fuels

Aerial fuels include all combustible material, live or dead located in the understorey and upper canopy of the trees. In plantation forestry aerial fuels will consist mainly of branches and foliage of trees and shrubs. These aerial fuels can support crown fires where sufficient surface fuels exist to increase the fire intensity (Trollope et al., 2004).

2.4 Fire behaviour

Fire behaviour refers to the release of heat energy during combustion as described by the rate of spread of the fire front, fire intensity, flame characteristics and other related phenomena such as crowing, spotting, fire whirlwinds and fire storms (Trollope et al., 2004).

Different factors affect fire behaviour such as the fire environment, the fuel types and loads, fire ignition, combustion and heat transfer as well as climatic conditions (Teie, 2005).

2.4.1 Combustion

Combustion is an oxidation process whereby a chain reaction occurs and heat energy is released during a fire that originated from solar energy via the process of photosynthesis. The combustion process is the result of a chemical chain reaction which is as follows: (Trollope et al., 2004).

$(C_6 H_{10} O_5)_n + O_2 +$ kindling temperature $= CO_2 + H_2O +$ Heat.

When heat is applied to fuel in the presence of oxygen, fire will be produced. This chemical reaction is called rapid oxidation (Teie, 2005).

2.4.2 Fire Triangle

The fire triangle illustrates the three essential elements necessary for combustion, namely, fuel, heat and oxygen. Removing one of the three elements makes it possible to extinguish a fire (Teie, 2005). The three elements of heat, oxygen and fuel affect fire and fire behaviour as well as fire suppression. The fire triangle consists of the elements as depicted below.

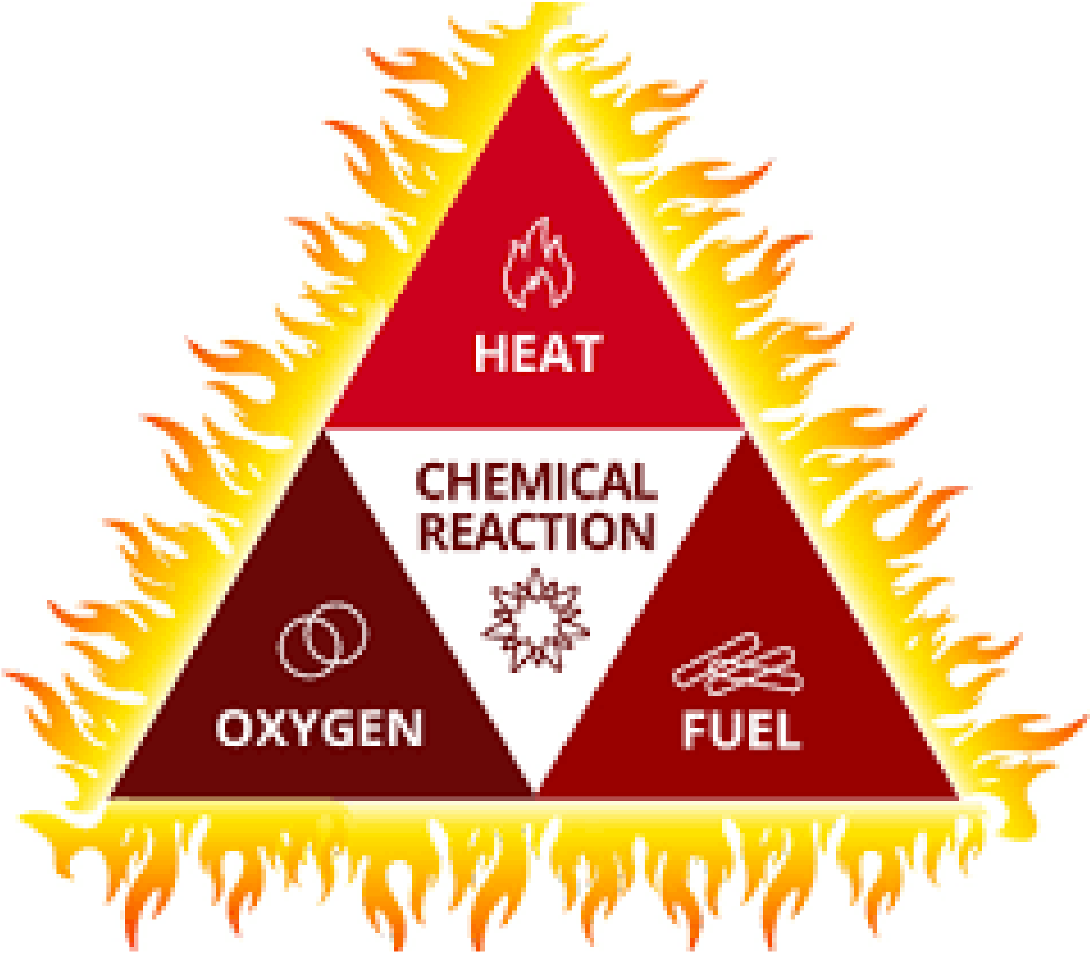


Figure 2.1: Fire triangle

2.4.2.1 Oxygen

A fire needs oxygen and reducing the amount of oxygen extinguishes a fire. Twenty one percent of the air is Oxygen and reducing this to 15% by smothering the fire, using sand or fire beaters will extinguish the fire (Trollope et al., 2004).

2.4.2.2 Fuel

Fire needs fuel for combustion to occur. Wildfires can be controlled by controlling the fuel component of the fire triangle. This can be done by confining the fire to specific areas, making use of fire breaks and fire lines. The fire line can be constructed by removing the surface fuels through hoeing to allow the mineral soil to be exposed or by creating a wet line whereby the fuel is wetted with water to prevent spread of fire beyond the fire line (Trollope et al., 2004).

Prescribed under canopy burning involves the control of fuel loads within compartments to have a positive effect of wildfire behaviour.

2.4.2.3 Heat

In order for a fire to ignite the fuel must be brought to its ignition temperature. If the heat drops below the ignition temperature, the fire is extinguished. In order to reduce the heat of fuels during fires water is most commonly used. Application of water to the burning fuel results in the reduction of heat to below the ignition temperature, resulting in the extinguishing of the fire (Trollope et al., 2004).

2.4.3 Fire ignition

Ignition of fires requires an ignition source. There are many sources of ignition such as lightening, bee hunters, arsonists, campfires, cigarettes, burning debris and sparks from exhausts and power lines (Trollope et al., 2004) (Teie, 2005). Other sources of ignition also exist such as friction during extraction of Eucalyptus tree lengths and poor mopping up after burning operations. Arson occurring on plantations close to communities can be problematic as children have been known to light fires in order to see the helicopters when aerial support arrives. Therefore awareness and education is critical.

Prescribed burning operations make use of drip torches to intentionally ignite fires. Drip torches are used to burn tracer belts, fire breaks as well as for during prescribed under canopy burning operations. The drip torch makes use of a mixture of petrol and diesel usually with a ratio of 30% petrol to 70% diesel. The petrol is for ignition and the diesel acts as an oil to allow the drip torch mix to have a suitable viscosity to allow the mixture to run but still burn and “carry” the flame.

The ignition temperature is the temperature of a substance at which it will ignite and continue to burn without any additional heat from another source. The moisture content of the fuel will affect the ease of ignition in dead fuels. As the moisture content of dead fuels decrease so too does the ease of ignition increase (Trollope., et al 2004).

The fuel particle size affects fuel ignition temperature. The smaller and finer the fuel particles the easier they are to ignite. Likewise, larger size, coarser fuel particles require more units of heat to be applied to the fuel to reach the ignition temperature (Teie, 2005), (Trollope et al., 2004).

Fuel temperature affects fuel ignition. The warmer the temperature of the fuel the less heat it will take to reach its ignition temperature and reach its ignition point. The cooler the fuel temperature the more heat will be required to bring it to ignition (Teie, 2005).

2.4.4 Heat transfer

The following three phases that proceed through fuels during forest fires is known as heat transfer:

Phase 1: Pre heating – Fuels ahead of the flame front are raised to their ignition point and involve the reduction of fuel moisture content and generation of flammable hydrocarbon gases.

Phase 2: Gaseous phase – The preheated fuels break down into gases and charcoal as flaming combustion occurs.

Phase 3: Combustion – The gases burn off and the residual charcoal is consumed by glowing combustion.

The amount of energy released during the flaming and glowing phases of combustion varies in relation to the types of fuels. Heavy fuels with low flames release a large proportion of heat energy via glowing combustion whereas light fuels release majority of heat energy as flaming combustion (Trollope et al., 2004).

The spread of wildfire or prescribed, controlled fires is dependent on heat transfer. Heat transfer involves three methods, namely, convection, conduction and radiation (Teie, 2005).

Combustion is a chain reaction and the maintenance of this chain reaction during a fire involves the transfer of heat energy via these processes of conduction, convection and radiation (Trollope et al., 2004).

2.4.4.1 Convection

Convection is the transfer of heat by the movement of hot air and other heated gases by the heating of air molecules. As these superheated air molecules come into contact with an object they transfer heat to it. This heat transfer occurs on all surfaces of the object. Convective heating results in the spread of fire (Trollope et al., 2004), (Teie, 2005).

Convective heating results in the preheating of the fuels in front of the flame front increasing fire intensity as heat is transferred to the fuels ahead of the flame front. Heat transfer is increased when fuels are upslope from the fire, when wind is fanning the fire or when fuels are closer together increasing radiated and conductive heat Trollope et al., (2004), (Teie, 2005).

2.4.4.2 Radiation

Radiation can be defined as the transfer of heat through space, in any direction, at the speed of light (Trollope et al., 2004). It is the movement of heat energy from the heat source in the form of waves. These waves travel in a straight line, passing through the air and when they strike an object they heat it (Teie, 2005). Radiation can result in the pre heating of fuels and the ignition of unburned fuels. Radiation can result in the spread of fire whether it is a wildfire or a controlled, prescribed under canopy burn.

2.4.4.3 Conduction

Conduction can be defined as the transfer of heat within a fuel unit, or from one fuel particle to another through direct contact (Trollope et al., 2004). This heat transfer happens within the material, molecule by molecule. The transfer rate is directly related to the composition of the object. Wood and other fuel types found in plantation areas are poor conductors of heat energy, therefore conduction does not play a major role in the spread of wildfire or controlled fires.

2.5 Fire intensity

Fire intensity is the rate of heat energy released during combustion. Teie (2005) explains that fire intensity can be measured in two ways namely by measuring the fire line intensity and flame length. Fire line intensity is the amount of heat released by a burning section of fire line, whereas flame length is measured by measuring the distance from the average flame tip to the middle of the flaming zone at the base of the flame.

Fire intensity is affected by various factors namely; fuel loading, compactness or arrangement of fuels, fuel moisture content, slope and wind speed (Teie, 2005).

- Fuel loading – is the amount of fuels available to burn. The amount of energy stored in the fuel affects the intensity of the fire, and the fuel load is an indicator of this. Luke and Mcarthur (1978) state that fuel load is regarded as one of the most important factors influencing fire behaviour because the total amount of heat energy available for release during a fire is related to the quantity of fuel (Trollope et al., 2004).
- Fuel load compaction has an impact on rate of spread and fire intensity. Fuel compaction refers to placement of pieces of fuel in relation to one another. A commercial pine plantation will typically have a compact fuel layer and this will result in a slower rate of spread with an even flame distribution whereas a well aerated fuel load with high vertical distribution will result in a rapid rate of spread with irregular flame length. Combustion is most favoured when fuel is loosely packed to enable oxygen to reach the flame zone, but dense enough to allow sufficient heat transfer to occur (Trollope et al., 2004).
- Fuel moisture content affects fire intensity. Fuel with an increased amount of moisture will require an increased amount of heat energy to decrease the fuel moisture content of the fuel to allow for combustion (Teie, 2005). The rate of

combustion is slower and fire intensity is lower in cold, moist fuels than for hot, dry fuels (Trollope et al., 2004).

- Slope and wind speed affect the rate of spread and therefore the fire intensity. Fires burn more intensely moving upslope or downwind as convective heating is more efficient. Preheating occurs more efficiently as flames are closer to fuels when fires are burning uphill (Trollope et al., 2004).

2.5.1 Measuring fire intensity

Frontal fire intensity is a valid measure of forest fire behaviour. Alexander (1980) defines fire intensity as the energy output rate per unit length of the fire front and is directly related to flame size. Numerically it is equal to the product of net heat and a spreading fires linear rate of advance (Alexander, 1980).

2.5.1.1 Byram's Fire Intensity

Byram's fire intensity is one of the most important and widely accepted metrics for measuring fire behaviour. In order to calculate the fire intensity, measurements of fuel consumption, heat of combustion and rate of spread are required. The active front of a forest fire has three characteristics namely it spreads; it consumes fuel and it produces heat energy in a visible flaming combustion reaction. Fire intensity is the single most valid characteristic of a fires general behaviour (Alexander, 1980).

Fire intensity (I) measured in units of kilowatts per metre (kW/m) can be determined by the equation:

$I=Hwr$

Where H is the fuel low heat of combustion in kilojoules per kilogram (kJ/kg), w is the weight of fuel consumed per unit area expressed in kilograms per square metre (kg/m^2) and r is the rate of spread in metres per second (m/s) (Alexander, 1980).

2.5.2 Remote devices

Electronic timing devices and thermo-loggers were developed to be used as remote timing devices. An electronic timer is an electronic clock that is activated when a solder connection is melted by the passing fire. A thermo-logger is a miniature thermo-couple, activated data logger that records the time of activation when the temperature exceeds 100˚C (McRae & Jin, 2004).

These devices are buried at grid points of the area to be burnt and the data is retrieved from these devices after the burning operation. This is the grid system approach and can be used to document the rate of spread of fire in a pre-planned area (McRae & Jin, 2004).

Two problems are associated with the grid system of recording fire spread. The first is that the rate of spread value obtained is an average of the area and is affected by the distance between the grid points and the remote devices. Therefore variables such as change in wind speeds, or fuel characteristics within the grid cannot be recorded.

The second problem is that the fire front is not always a continuous linear front, it can be erratic and develop fingers. The top point of a finger may pass the remote device at a grid point, before the bottom part of the finger reaches the device and activates it. To overcome these problems many remote devices would have to be placed throughout the grid, and this may be impractical (McRae & Jin, 2004).

2.5.3 Infrared technology

Infrared technology can be used to document the temperatures of the fire front as well as the rate of fire spread. Infrared cameras can record temperatures up to 1500 degrees Celsius which is within the temperature range of forest fires. Camera sensors can provide data within 2% of actual temperatures. Infrared cameras can be used from above with helicopters or at ground level with handheld or mounted cameras (McRae & Jin, 2004).

Infrared image processing allows quantification of various fire behaviour parameters such as fire front location times, rate of spread and spatial distribution of temperatures. Further processing will allow for calculation of fire radiative power (kW/m^{-2}) as well as fire intensity (kW/m^{-1}) (McRae & Jin, 2004).

Infrared technology can assist with the determination of fire intensity (kW/m^{-1}) by using information from the different variables. Fire front temperatures can be determined from the infrared imagery. Fire rate of spread can be determined from the infrared imagery coupled with GIS information to determine the rate of spread in m/s. Fuel consumption information can be determined through means of fuel load measurements before and after the fire. With this information the fire intensity can be calculated using Byram's fire intensity formula.

2.6 Fire behaviour models

Behave Plus is a fire behaviour prediction and fuel modelling system. Behave Plus can be used before applying a prescribed burning operation to predict fire behaviour making use of fuel models which represent the fuels found in the area that will be burnt. Once the correct fuel model has been selected and the fuel model information has been captured it is possible to specify the climatic and topographic variables and continue with the fire behaviour prediction procedures (Heinsch & Andrews, 2010).

Behave Plus consists of many models that are grouped into logical groups called modules. The system consists of nine modules namely, surface, crown, safety, size, contain, spot, scorch, mortality and ignite. Each module predicts fire behaviour related to the specific module such as surface fire behaviour for the surface module or crown fire behaviour for the crown module and tree mortality for the mortality module (Heinsch & Andrews, 2010).

2.7 Stand responses to prescribed under canopy burning

Previous studies conducted by Bird and Scholes (2005) have shown that prescribed under canopy burning operations under low heat in *Pinus patula* compartments resulted in the reduction of fuel loads with no significant effect on tree growth (Bird & Scholes, 2005). Compartments that experienced a high intensity burn experienced a negative effect on tree growth after a period of 36 months. A high intensity fire will occur when temperatures are higher, relative humidity is lower, and fuel moisture content is lower and this results in increased fire line intensity. In the study conducted by Bird and Scholes (2005), the intensity averages were measured to be between 761 kW/m for a higher intensity burn compared to 134 and 277 kW/m for low and medium intensity fires respectively (Bird & Scholes, 2005).

Diameter at breast height (DBH) measurements were recorded in plots that received different intensity burns. No significant difference was recorded between control plots or low intensity plots, however trees in the plot that received high intensity burns showed an average increase of 7.8% compared to a 10.3% increase for trees in the control, no burn plots (Bird & Scholes, 2005).

Basal area increment (BAI) measurements again showed that high intensity burning operations have a negative effect on tree growth. Measurements taken in the first year subsequent to burning show ranges of 1.7m^2/ha/yr in high intensity plots compared to 2.8m^2/ha/yr in no burn, control plots. The study by Bird and Scholes (2005) shows the critical importance of the effect of fire intensity on tree growth (Bird & Scholes, 2005).

2.8 Tree damage

Tree damage is usually divided into three categories, namely cambium damage, crown scorch and root damage (Gresse C. , 2015). In areas where the fire burnt through to mineral soil, root damage is automatically assumed. Root damage can be quantified by grouping these roots into different root damage classes.

Cambium damage is determined by placing a piece of damaged cambium in a tetrazolium solution. On trees where resin is observed, cambium damage is automatically observed. Crown scorch is determined by observation of trees, observing when scorched needles turn brown (Gresse C. , 2015).

Data from previous research in Mpumalanga shows that root damage was observed to have occurred in *Pinus patula* compartments after under canopy burning treatments. The root damage was divided into classes of severity and the damage varied between 0-70%. Class 0 is the least severe and class 4 is the most severe class of root damage (Gresse C. , 2015). In Gresse's (2015) study, within the damage class of 3 and 4 a maximum of 10% root damage was observed and within classes of 0 and 1 a maximum of 70% root damage was observed. Root damage in *Pinus elliottii* sites occurred and varied between 5 and 25% of trees within the trial.

Cambium damage was only observed in *Pinus patula* sites ranging between 8 – 19% of trees damaged, however cambium samples were tested in tetrazolium solution and no dead cambium was found (Gresse C. , 2015).

2.9 Conclusions from the literature review.

The factors driving fire behaviour in pine forests are fairly well understood and there is a small but growing body of knowledge on the degree of fire resistance among commercially important pine species. However, South African forestry lacks information on the intensities of fires used in controlled burning. It also lacks information on tree damage during controlled burning and the effect of repeated under canopy burning on fuel load reduction, and on stand growth response.

3. Methodology

3.1 Study area

Three plantations have been identified where previous research has been carried out. The three plantations all occur in the Mpumalanga province of South Africa. These plantations are SAFCOL Berlin plantation which is situated near Kaapsehoop, SAFCOL Nelshoogte plantation which is situated between Barberton and Badplaas and SAFCOL Blyde plantation which is situated near Graskop. Berlin and Nelshoogte plantations are situated in the Highveld areas of Mpumalanga whereas Blyde plantation is in the lowveld region of Mpumalanga.

Due to the higher altitude of the highveld areas, temperatures are typically cooler with a regular occurrence of frost whereas the lowveld areas, due to the lower altitudes experience warmer conditions with a lesser frequency of frost occurrence.

The trial plots in the three plantations all occur in pine plantations and a number of plots have been selected in each compartment to ensure a sufficient amount of replications are available.

Figure 3.1: Satellite image indicating position of the 3 trial sites.

3.2 Trial site layout

On each plantation a specific number of plots were identified and marked. Berlin plantation has a total of nine plots of which three were never burnt, three were burnt on one occasion and three were burnt twice (Table 3.4). This enables the research to compare the impact of burning with regards to tree and site responses in areas never burnt compared to areas that were once burnt and areas that received repeated burning. The plots that had previously received one or two burning treatments during the period 2006 – 2015 received a further burning treatment in 2019 to allow comparison of control plots with plots that have received two and three burning treatments respectively.

The same plot layout exists for Nelshoogte (Table 3.9), however Blyde is different as there are no unburnt control plots. Six plots are available whereby three have previously been burnt once and three have been burnt twice whereby the twice burnt plots received a further burning treatment (Table 3.1 and Gresse, 2015).

The plots per trial site were replicated three times and each replication was positioned on a different topographical position within the trial site area specifically for Berlin and Nelshoogte plantations where the trial site areas were sloping from top to bottom.

The following factors were compared with the trials and treatments:

- Stand growth responses
- Forest floor mass (fuel loads)
- Tree damage
- Litter fall rate

The control plots refer to plots that received no burning treatments whilst burnt plots refer to plots that were burnt twice or three times respectively as is the case for the Berlin and Nelshoogte trial sites. The Blyde burnt plots received burning treatments once and three times respectively.

Table 3.1: Compartment information for plots on three trial sites containing under canopy burnt and unburnt treatments in Mpumalanga.

Plantation	Comp no.	Species	Plant date	SI20	TPH	Soil	Slope	Altitude	Burn/control
Berlin	M31	P.patula	1995	23.1	250	Inanda	0-30	1659	Control
Berlin	M29	P.patula	1995	23.2	245	Kranskop	0-30	1656	Burn
Blyde	A87	P.elliottii	1995	27.4	312	Hutton	0-30	1414	Burn
Nelshoogte	E38	P.patula	1989	24.9	269	Inanda	0-30	1408	Control
Nelshoogte	E28a	P.patula	1990	25.7	284	Inanda	0-30	1407	Burn

3.2.1 Plot layout

Each plantation consists of different trial sites which occur in specific plantation compartments. Each trial site consists of different plots namely, unburnt plots, once burnt plot, twice burnt plots or plots that have been burnt on three occasions.

3.2.1.1 Berlin plantation

Berlin Plantation is situated in Mpumalanga near the town of Kaapsehoop (Figure 3.3). The trial site is situated at 1650m above sea level and the soil type is characterised dominantly as a dolomite-derived soil. The slope is within the range of 20-35%.

Compartments wherein the trial sites are situated received various silvicultural treatments, namely thinning and pruning at different ages. Table 3.2 and Table 3.3 below details the silvicultural treatments on the Berlin plantation trial sites.

Table 3.2: Previous treatments conducted in compartment M31 – Berlin.

Activity	Age	TPH	Activity	Age	Height
Thin 1	8.00	417	Prune 1	6.00	1.50
Thin 2	14.17	261	Prune 2	7.01	3.00
			Prune 3	9.10	7.50
			Prune 4	11.33	8.50

Table 3.3: Previous treatments conducted in M29 – Berlin.

Activity	Age	TPH	Activity	Age	Height	Activity	Year	FF mass reduction
Thin 1	8.10	650	Prune 1	5.00	1.50	Burn 1	2007	Unknown
Thin 2	12	230	Prune 2	6.01	3.00	Burn 2	May-15	50 - 36 t/ha
			Prune 3	8.33	5.00			
			Prune 4	9.30	6.50			
			Prune 5	10.08	9.50			

The plots within the trial sites at Berlin Plantation were each measured (Table 3.4), and pegs used to demarcate the four corners of the plot. On one corner of each plot a label was attached to the peg to assist with identification of the plot (Figure 3.2).

Table 3.4: Berlin trial site - Plot information relating to plot size, trees per plot and SPHA.

Plantation/Berlin	Plot	Plot size m²	Trees/plot	Density/SPHA
Unburnt	1A	1172	29	248
Unburnt	2A	1144	28	245
Unburnt	3A	935	24	257
Once burnt	1B1	1122	25	223
Once burnt	2B1	1140	29	254
Once burnt	3B1	932	25	268
Twice burnt	1B2	1043	28	268
Twice burnt	2B2	959	24	250
Twice burnt	3B2	894	20	224

Figure 3.2: Plot identification.

Figure 3.3: Berlin trial site location.

3.2.1.2 Blyde plantation

The trial site on Blyde plantation is situated within a *Pinus elliottii* compartment which was planted in 1996. The trial site is 1400m above sea level and the compartment is on level terrain with the slope class within the range of 0-12% with a dolomitic soil type (Figure 3.4).

The compartment received a high pruning at 10 years of age and two thinning operations took place at ages 12 and 16. The compartment on the Blyde site received under canopy burning treatments in 2007 and 2014 (Table 3.5). The plots were pegged, labelled and measured and trees per plot counted to determine SPHA (Table 3.6).

Table 3.5: Previous treatments conducted in A87 – Blyde.

1	Activity	Age	TPH	Activity	Age	Height	Activity	Year	FF mass reduction
	Thin 1	12.00	369	Prune 1	4.00	2.00	Burn 1	2007	Unknown
	Thin 2	16.17	276	Prune 2	5.01	3.50	Burn 2	Feb-14	18 - 10 t/ha
				Prune 3	6.67	5.00			
				Prune 4	7.75	6.50			
				Prune 5	9.60	7.50			
				Prune 6	10.00	8.50			
				Prune 7	10.17	9.50			

Table 3.6: Blyde trial site - Plot information relating to plot size, trees per plot and SPHA.

Plantation/Blyde	Plot	Plot size m²	Trees/plot	Density/SPHA
Once burnt	1B1	1120	38	339
Once burnt	2B1	1022	31	303
Once burnt	3B1	1089	32	294
Twice burnt	1B2	1254	41	327
Twice burnt	2B2	1037	35	338
Twice burnt	3B2	1083	30	277

Figure 3.4: Blyde trial site location.

3.2.1.3 Nelshoogte plantation

The Nelshoogte trial sites are within *Pinus patula compartments (Figure 3.5).* Nelshoogte plantation is situated in the Highveld region of Mpumalanga between the towns of Badplaas and Barberton. The trial sites are 1400m above sea level and the slope class ranges between 12% – 20% with the dominant soil type being characterised by granite parent material.

Three thinning operations took place at ages 8, 13 and 17 and the compartment received pruning treatments up to a height of 7.0 m at age 11 in the burnt plots and age 12 in the control plots respectively (Table 3.7 and Table 3.8). The plots on the Nelshoogte trial site were pegged, labelled, and measured. Trees per plot were counted and this enabled the calculation of trees per hectare (Table 3.9).

Table 3.7: Previous treatments conducted in E28a – Nelshoogte.

Activity	Age	TPH	Activity	Age	Height	Activity	Year	FF mass reduction
Thin 1	8.00	645	Prune 1	6.00	1.50	Burn 1	2007	Unknown
Thin 2	13.00	409	Prune 2	7.01	3.00	Burn 2	May-15	65 - 48 t/ha
Thin 3	17.53	273	Prune 3	8.02	5.00			
			Prune 4	11.03	7.00			

Table 3.8: Previous treatments conducted in E38 – Nelshoogte.

Activity	Age	TPH	Activity	Age	Height
Thin 1	8.00	650	Prune 1	4.00	1.50
Thin 2	13.00	484	Prune 2	7.01	3.00
Thin 3	17.53	249	Prune 3	9.02	5.00
			Prune 4	12.03	7.00

Table 3.9: Nelshoogte trial site - Plot information relating to plot size, trees per plot and SPHA.

Plantation/Nelshoogte	Plot	Plot size m^2	Trees/plot	Density/SPHA
Unburnt	1A	1465	36	246
Unburnt	2A	1503	43	286
Unburnt	3A	1543	41	266
Once burnt	1B1	1504	40	266
Once burnt	2B1	1489	43	289
Once burnt	3B1	1503	39	259
Twice burnt	1B2	1529	47	307
Twice burnt	2B2	1502	44	293
Twice burnt	3B2	1378	44	319

Figure 3.5: Nelshoogte trial site location.

3.2.1.4 Stand density

The stand density is measured in terms of stems or trees per hectare. To understand the degree of intraspecific competition in a plantation, the relative density (RD) of the compartment can be calculated. The relative density is defined as the basal area divided by the quadratic mean DBH of the compartment (Curtis, 2010). The relative density is divided into five classes indicative of increasing competition (Table 3.10).

Table 3.10: Relative density classification of tree competition intensity.

Density class	Rating	Description
1	0 - 1.5	Zone of low levels of competition
2	1.5 - 3.0	Zone of fair levels of competition
3	3.0 - 6.0	Zone of increasing competition
4	6.0 - 12.0	Zone of severe competition
5	12.0 +	Zone of imminent mortality

The relative density of each compartment indicates the health of the stand in terms of competition for resources; namely water, light and nutrients. The RD is calculated using the following formula: RD = basal area / $(Dq)^{0.5}$

If the DBH measurements of each plot in each compartment and the plot sizes are known, it is possible to calculate the quadratic mean DBH after which the basal area can be calculated and these figures can be used to calculate the relative density (Kotze & du Toit, 2012).

3.3 Sampling techniques

The following sampling techniques were used for this study.

3.3.1 Fire breaks

Fire breaks in the form of cleared strips within the forest floor of the compartment were used to designate the areas that needed to be burnt and the areas that did not need to be burnt.

The fire breaks were constructed manually using rake hoes, hoeing away the surface material down to mineral soil. The fire breaks were approximately one meter in width and were constructed prior to the burning operation taking place (Figure 3.6).

Figure 3.6: Firebreak at Berlin trial site.

3.3.2 Prescribed under canopy burning

The most recent burning operations took place during the months of April and May 2019. Previously the trials sites received burning treatments during 2014 and 2015 and prior to this, burning treatments occurred during the years of 2006 and 2007.

The Blyde trial site was most recently burned on the 24 the April 2019. The average temperature was 25.9 degrees Celsius, and the humidity was high with an average of 57.2%. Fuel moisture content of 22.9% in the litter (L layer) and 80.1 % in the fermentation and humus (F&H) layers were measured.

The Berlin trial site received a burning treatment on the 7th May 2019. On the day of the burn the average temperature was 19.3°C, with an average relative humidity of 73.7%. The L layer had a fuel moisture of 20.2% and the combined F and H layers had a fuel moisture content of 121.4%. Due to the high humidity and low temperatures it was difficult to conduct the burns in these trial sites. Previous attempts had taken place earlier in May 2019 as well as in late April 2019 however on both these occasions the conditions did not allow the trial sites to burn. On the third attempt on the 7th May a decision was taken to aerate the compact litter layer in the trial sites to assist it to burn. This took place using rake hoes to lift the litter layer before starting the burn. A strip pattern of ignition was used to increase the fire intensity which resulted in a uniform burn. The below images depict the aerated litter layer (Figure 3.7) as well as the strip method of ignition (Figure 3.8) and the end result, a uniform burn (Figure 3.9).

Figure 3.7: Aeration of litter layer at Berlin trial site.

Figure 3.8: Prescribed under canopy fuel load reduction burning operation on Berlin trial site.

Figure 3.9: Uniform burn at Berlin trial site.

The Nelshoogte trial sites received a burning treatment on the 13th May 2019. The average temperature on the day of the burn was 25.9°C and the average relative humidity was 32.8%. The average measured fuel moisture content of the L layer was 16.9% and 55.2% for the combined F and H layers. The trial sites on Nelshoogte plantation were difficult to burn in the morning hours, however as the day progressed and the RH decreased and temperatures increased the trial sites burnt successfully with no need to aerate the L layer within the plots. A combination of strip and spot ignition techniques were used depending on the time of the day and the rate of spread. As the temperatures increased and the RH decreased, the rate of spread and fire intensity increased and the strip method of ignition was replaced with the spot method of ignition. The below photos show the ignition patterns (Figure 3.10) as well as the end result, a uniform burn (Figure 3.11).

Figure 3.10: Burning patterns at Nelshoogte trial site.

Figure 3.11: Uniform burn at Nelshoogte trial site.

During the under canopy burning operation, data was collected. Table 3.11 indicates the different variables that were measured. Measurements were taken at the beginning of the burn and recorded every thirty minutes throughout the duration of the under canopy burning operation. Seeing that the treatments of the trials reported in this thesis are the burning events, a brief summary of the fire intensity and fire conditions are given here (Table 3.11).

Table 3.11: Measured average data affecting burning conditions and fire intensity during prescribed burning operations (Standard error in brackets).

Plantation	Blyde	Nelshoogte	Berlin
Temp °C	25.9 (1.20)	26.0 (0.19)	19.3 (0.44)
RH %	57.2 (4.0)	32.8 (0.73)	73.7 (1.34)
Wind speed m/s	0.5 (0.1)	0.7 (0.07)	1.0 (0.09)
Fuel moisture % L	23.0 (1.2)	16.9 (0.37)	20.2 (0.70)
Fuel moisture % F & H	80.1 (6.4)	55.2 (2.87)	121.4 (2.60)
Fuel load t/ha	27.7 (0.3)	33.9 (0.26)	30.6 (0.88)
Fire front flame height	<25cm	<25cm	<25cm
Rate of spread m/s	0.001	0.005	0.005
Fire front heat °C	504 (23.0)	542 (10.95)	562 (12.37)

3.3.2.1 Fuel moisture content

Samples of the forest floor fractions were taken before commencement of the burning operation. The forest floor samples were divided into two fractions, namely the litter layer and the combined fermentation and humus layers. The fuel moisture was measured using a portable fuel moisture meter. The samples were sealed in plastic bags after which they were weighed and then oven dried until a constant mass was achieved. The following equation was used to determine the fuel moisture content (Reeb & Milota, 1999).

$$MC = \frac{\text{initial weight} - \text{oven dried weight}}{\text{Oven dried weight}} \times 100\%$$

3.3.2.2 Burning techniques

All trial sites were burnt manually making use of drip torches. The drip torches contain a mixture of petrol and diesel to allow ignition and spread. The two types of ignition techniques used at the different trial sites were spot ignition techniques and strip method techniques and a combination of both.

The fire line was started from the fire break in the trial site. In the spot ignition technique, the drip torch operator releases a spot and then walks two to three meters along a predetermined line before releasing another spot. Alternatively, the drip torch operator can pull a continuous ignition line with the strip ignition method. The spot ignition technique results in a less intense rate of spread and a lower fire intensity and is therefore considered the safest method.

3.3.2.3 Forest floor sampling

Two forest floor samples were taken in each research plot of each trial site. Each sample was collected by making use of a measuring tape and measuring a 50 cm by 50 cm square and by using a shovel digging down to mineral soil (Figure 3.12). The forest floor layers were sampled individually separating the litter layer from the combined fermentation and humus layers. The separated samples were sealed in plastic bags, and the samples were oven dried at a constant temperature.

3.3.2.4 Forest floor mass determination

Forest floor mass was measured in each of the trial sites using two methods. The physical samples that were taken were dried at a constant temperature until reaching a point of constant weight. The oven dried mass was expressed in tons per hectare. Another method used involved the random measuring of forest floor depth using a ruler, and then applying species specific depth-mass regressions to calculate the forest floor mass in the respective trial sites. In order to measure the depth a shovel was used to dig open a space from the surface fuel down to mineral soil. The ruler could then be placed vertically down to the mineral soil and the depth measured in centimetres. Twenty depth measurements were taken per plot and averaged. The forest floor mass was then calculated using the averaged depth measurement and the depth mass regression to calculate the forest floor mass in tons per hectare (Ross & Du Toit, 2004). Forest floor mass determination was carried out before the burning operation commenced in April and May 2019 as well as after the burning operations in June 2019.

Figure 3.12: Forest floor mass sampling.

3.3.2.5 Categorisation of burning event labels.

Controlled burning treatments were implemented at intervals that can be classified as early, middle and late in the allowable window of prescribed burning (roughly age 13 – 30 in Pine stands). Since forest floor mass was recorded before and after controlled burning treatments were implemented in these three windows, it allowed the calculation of forest floor reductions in the following combinations:

- Unburnt
- Early and mid-rotation burning events (E + M) – approximately 14 and 21 years
- Early plus late - rotation burning events (E + L) - approximately 14 and 29 years
- Three burning events (E + M + L) - (early, middle and late in the burning window)

Table 3.12 is applicable only to forest floor mass. In 2019 forest floor samples were taken before and after the prescribed burning treatments. The burning events were labelled to categorize the burning event as an early, mid or late burn or a combination of two or three of the events.

Table 3.12: Burning event labels assigned to measurements of forest floor mass emanating from sampling times before and after implementation of the twice and three times burning events in 2019.

Treatment name	Mean age of all stands at time of treatment implementation	Sample collected #	Number of burning events at time of sampling	Burn event label*
Unburnt control	14	Before treatment	Unburnt	Control
Twice burnt	14 and 27	Before 2019 treatment	1	E
	14 and 27	After 2019 treatment	2	E + L
Three times burnt	14, 22 and 27	Before 2019 treatment	2	E + M
	14, 22 and 27	After 2019 treatment	3	E + M + L

Note that all samples were taken in 2019, when stands were 24 years (Blyde, Berlin) 29 years (Nelshoogte) and 30 years (Nelshoogte), i.e. mean age of approximately 27 years.
*(where E = early, M = mid and L = late in the allowable burning window which extends from 13 – 30 years of age. The labels are only applicable to the forest floor samples.

3.3.3 Litter fall rate

Litter fall was measured using litter fall traps. The litter fall traps were made of 50 cm by 60 cm wooden frames. On the inside of the frame is shade cloth that allows for the capture of the needles as well as drainage of the water. Litter fall traps were placed in the different plots after the completion of the burn.

The litter fall was collected monthly for a period of seven months from June 2019 until December 2019. The litter from each trap was collected and placed in plastic bags and weighed at a constant temperature until dried to its oven dried mass. The litter fall was then calculated to express the figure in tons per hectare.

3.3.4 Tree damage

Inspection of trees per plot took place to determine if any tree damage occurred in the form of crown scorch, root damage and tree mortality. This is critical to determine the impact of under canopy burning on stand health.

3.3.4.1 Tree mortality

Tree mortality was observed by visual observation. Each tree in each plot was counted and numbered before the burning operation took place. Another count took place six months after the burning operation to determine if any mortality occurred. Dead trees were defined as trees with zero % green needles six months after the burning operation took place.

3.3.4.2 Crown damage

Crown scorch refers to the degree of scorch experienced by the crown of the tree expressed as a percentage. No scorch was detected during implementation of the 2019 fires but the scorch intensities recorded in earlier treatments were calculated as follows by Gresse (2015): The percentage of the number of scorched trees was multiplied by the midpoint of the average scorched crown height per plot to determine the total percentage of crown scorch per plot.

The following categories were used to classify the crown scorching percentage.

- Low damage (< 25% crown scorch)
- Medium damage (>25%<50% crown scorch)
- High damage (>50%<75% crown scorch)
- Very high damage (>75% crown scorch)

3.3.4.3 Root damage

Root damage was determined after the burning operation. Areas within the plot where the forest floor was burnt down to the mineral soil was visually checked to see if any roots were burnt through. Ten trees per plot were randomly inspected in these areas to determine root damage. The number of trees that experienced root damaged per plot were upscaled and expressed as the number of root damaged trees per hectare. Roots that were damaged were classified according to the following root thickness classification.

- 2 – 10mm = medium roots
- 10 – 25mm = coarse roots
- >25mm = very coarse roots

The severity of root damage was determined using the following classification system:

Table 3.13: Root damage severity classification.

Damage class	Description
0	Did not burn to mineral soil, no root damage
1	Less than 4 medium roots burned through
2	4 or more medium roots burned through
3	2 or more coarse roots burned through
4	1 or more very coarse root(s) burned through

If it did not burn to the mineral soil no root damage was recorded. If it did burn down to mineral soil the roots were inspected to see if any roots were burnt. Only roots that were burnt through were considered when determining root damage. The number of medium to very coarse roots were counted and the trees were grouped according to root damage classification system as indicated in Table 3.13.

3.3.5 Growth responses

The diameters of all trees within each trial site were measured using diameter tapes. The heights of 30 trees within each trial site were measured and a DBH height regression used to determine the remaining heights of all trees on each plot at that specific site (Figures 3.13, 3.14 and 3.15). Making use of the diameter and height, a volume formula for the relevant species was used to determine the tree volume of each tree. The dimensions of the plots were measured to determine the volume per plot and therefore enabling the calculation of volume per hectare of each trial site.

In instances whereby tree mortality occurred between 2014 and 2020, the tree was disregarded for the purpose of the volume calculation. It is noted that tree mortality occurred in the trial sites of Berlin and Nelshoogte plantations in various plots. Tree mortality occurred in Nelshoogte in the control plots and well as in plots that received burning treatments.

No tree mortality occurred in the Blyde trial site. Due to the fact that no consistent correlation between burning treatments and tree mortality was evident, the trees that did not survive were removed when determining the volume per plot and PAI.

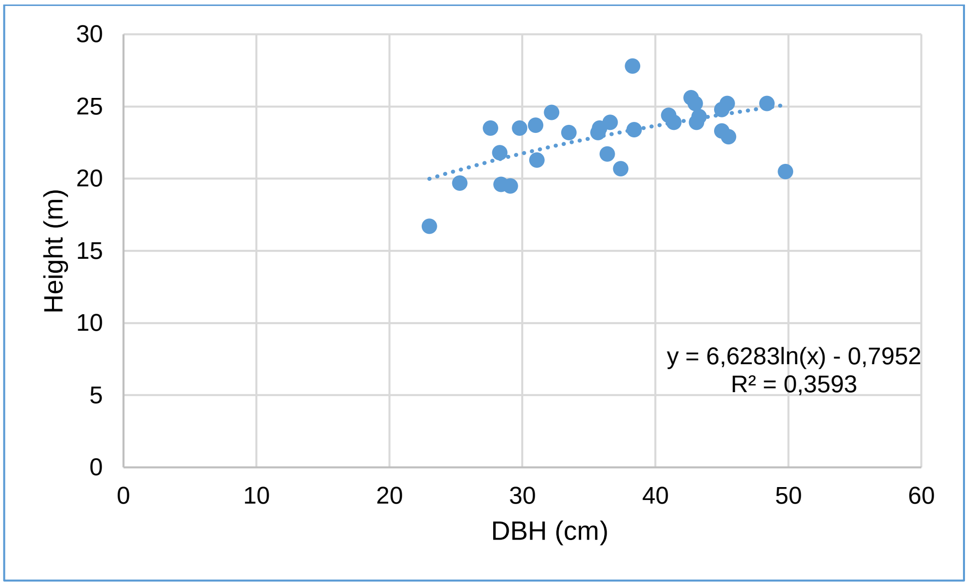


Figure 3.13: Blyde trial site DBH Height regression.

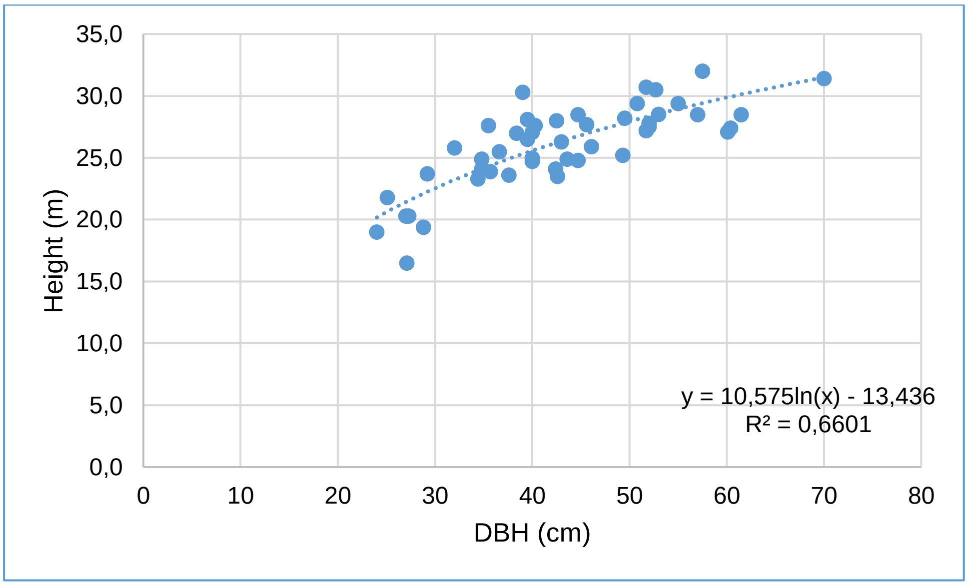


Figure 3.14: Nelshoogte trial site DBH Height regression.

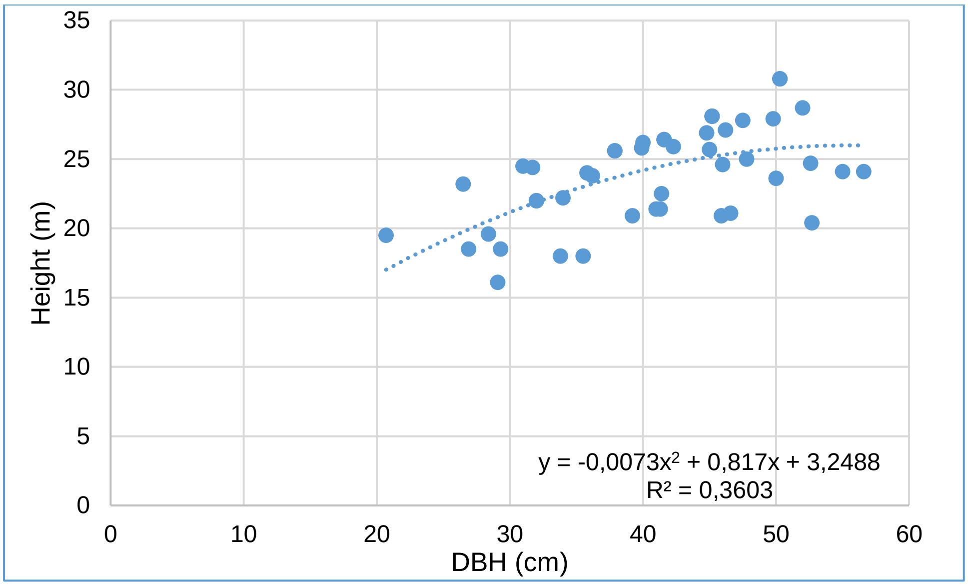


Figure 3.15 Berlin trial site DBH height regression.

The DBH and height information was used to calculate the volume per tree using the volume formula from the South African Forestry handbook, 5th edition.

The formulas are as follows:

Pinus patula stem volume =EXP (-13.4694+2.4396*LN (DBH+8) +1.3254*LN (Height))

Pinus elliottii stem volume=EXP (-10.677+1.9306*LN (DBH+0) +1.1567*LN (Height))

(Bredenkamp B. V., 2012)

Where:

Stem volume is expressed in m^3 up to a thin-end diameter of 7 cm, DBH is the diameter at breast height, measured in cm and the height is total tree height measured in meters (Bredenkamp, 2012).

The volume per tree was summed to calculate the standing volume per plot, after which the volume per plot was divided by the area of the plot in m^2 and multiplied by 10 000 m^2 to express it as a volume per unit area in m^3/ha . Comparisons could then be made regarding the stand volume growth for the different years; namely 2014, 2016 and 2018. The growth increment over each time period is referred to as the periodic annual volume increment.

4. Results

4.1 Burning conditions and fire intensity

During the burning operation, measurements were taken throughout the duration of the burn. The measurements include the temperature, RH, wind speed, fuel moisture content of the L layer as well as the F&H layer combined as well as the fire front heat (Table 4.1).

The following findings were evident from the data collected:

4.1.1 Nelshoogte plantation

- The trial sites were burnt on the 13th May 2019, this is outside the recommended under canopy burning window. The recommended under canopy burning window occurs in the rainy season during the months from November to end of March. This is to ensure sufficient rainfall to ensure that the FMC of the L and F&H layers are sufficient. (SAFCOL, Intergrated management system, 2018)
- The Nelshoogte trial sites consist of *Pinus patula* plots
- On the day of the burn the RH was between a range of 29% and 36%. The temperatures on the day were between a range of 25°C and 27°C.
- The wind speeds were insignificant
- The FMC of the L layer was below 20% and as low as 15%, while the FMC of the F&H layer was within a range of 35 – 65%
- The above conditions on the day of the burn resulted in a maximum fire front heat of 567°C.

Previous and current under canopy burning standards would describe the above conditions on the day of the burn as not ideally suited for under canopy burning due to the high temperature and low RH. It must be noted that the burn took place and was of a low intensity. Crown scorch was not evident, the fire did not burn in an uncontrolled manner, only the top layer of the fuel, namely the L layer fuel fraction was consumed and the F&H layers were too moist to sustain a fire. It is evident from these results that the FMC of the F&H layers is of utmost importance.

4.1.2 Berlin plantation

- The under canopy burning treatment took place on Berlin plantation on the 7th May 2019
- The Berlin trial sites consists of *Pinus patula* plots
- The air temperature ranges were between 17 and 21°C on the day of burn
- The RH range was between 69 and 83% on the day of burn
- Berlin plantation trial sites are situated on a high altitude site where it is typically cool and misty
- Maximum wind speed of 1.5 m/s was measured
- The FMC of the L layer was between 17 and 22% while FMC of the F&H layer was high between 116 and 135%
- The maximum fire front heat measured was 607°C
- The above conditions were not conducive for under canopy burning in *Pinus patula* compartments.
- The trial sites could not sustain a fire and the L layer had to first be manually aerated using rake hoes to lift the needle layer to allow sufficient aeration
- After the aeration took place the L layer did sustain a fire and resulted in a uniform burn.

It is evident from the data collected on the day of the burn at the Berlin trial site that *Pinus patula* (due to the nature of the compacted needle layer) requires conditions with a lower RH and higher temperatures to allow it to sustain a fire. The FMC of the L Layer was suitably dry, however it could still not sustain a fire with the RH being above 60%. Only the litter layer was consumed during the burn and only after aeration of the litter layer took place.

4.1.3 Blyde plantation

- Blyde plantation under canopy burning treatment took place on the 24 April 2019
- Blyde plantation trial site consists of *Pinus elliottii* trial site plots.
- The burning operation took place in the afternoon and the temperatures decreased rapidly as the sun set. The range of temperatures were between 19 and 27°C with the RH ranging from 53% and increasingly to 79% as the temperature decreased later in the afternoon.
- The FMC of the L layer was within a range of 22 – 28% with the FMC of the F&H layers within a range of 88-96%
- The fuel load ranged between 27 and 29 tons/ha
- The maximum fire front heat recorded was 608°C on the day of the burn

From the data collected it is evident that *Pinus elliottii* can sustain a fire with higher RH conditions. The fire continued to sustain itself with an RH of 60%, however later in the afternoon when the temperature decreased and the sun set the RH increased to 79%. At this stage the fire could no longer adequately sustain itself and to complete the burn much drip torch mix was used and a strip pattern of ignition was used. With this intervention the fire could only sustain itself for a limited period of time.

Table 4.1: Burning conditions measured on day of burn and the effect on intensity

Trial site	Plot	Temp	RH %	WS m/s	FMC % L	FMC % F & H	Fuel load t/ha	FFH °C	Comments
Nels	1B1	25.0	36.2	0.9	15.9	54.9	48.2	567.7	High temps, low RH, Low FMC L layer, uniform burn
Nels	2B1	25.9	30.7	0.7	17.5	65.3	54.6	499.0	High temps, low RH, Low FMC L layer, uniform burn
Nels	3B1	25.6	35.1	0.5	15.9	59.2	40.5	524.0	High temps, low RH, Low FMC L layer, uniform burn
Nels	1B2	26.9	35.1	1.0	17.2	61.2	41.7	576.3	High temps, low RH, Low FMC L layer, uniform burn
Nels	2B2	26.3	30.2	0.6	18.6	35.4	38.8	527.3	High temps, low RH, Low FMC L layer, uniform burn
Nels	3B2	26.2	29.4	0.4	16.4	55.3	34.5	555.3	High temps, low RH, Low FMC L layer, uniform burn
Berlin	1B1	20.6	69.3	1.5	20.6	122.0	34.4	535.3	Medium temps, high RH, high FMC F&H, only burned after aeration
Berlin	2B1	17.1	77.7	0.8	19.8	116.2	34.5	547.0	Medium temps, high RH, high FMC F&H, only burned after aeration
Berlin	3B1	20.0	69.0	0.9	17.8	116.6	33.1	607.7	Medium temps, high RH, high FMC F&H, only burned after aeration
Berlin	1B2	21.2	73.3	0.4	21.0	135.2	30.4	558.5	Medium temps, high RH, high FMC F&H, only burned after aeration
Berlin	2B2	19.3	69.7	1.0	22.0	120.0	24.2	587.0	Medium temps, high RH, high FMC F&H, only burned after aeration
Berlin	3B2	17.7	83.0	1.2	20.0	118.2	27.2	538.7	Medium temps, high RH, high FMC F&H, only burned after aeration
Blyde	1B2	19.9	79.0	1.0	24.5	88.2	29.5	608.8	High RH, could not burn sufficiently
Blyde	2B2	27.0	59.1	0.7	22.3	86.0	27.8	565.8	High temps, medium RH, could burn sufficiently
Blyde	3B2	26.9	53.2	0.6	28.0	96.7	27.1	523.8	High temps, medium RH, could burn sufficiently

4.1.4 Fire intensity

Fire intensity was modelled using the Behave Plus 6 fire intensity modelling programme. The input variables such as the fuel moisture content, wind speed and fuel load were taken from infield measurements. Table 4.2 below shows the fire intensity output variables for the three experimental trial sites.

Table 4.2: Fire intensity output variables using Behave Plus fire intensity modelling programme.

Behave Fire Intensity			
Output variables	Nelshoogte	Berlin	Blyde
Surface rate of spread	0.1 m/min	0.2 m/min	0.1 m/min
Surface fire heat per unit area	4809 kJ/m²	4071 kJ/m²	3080 kJ/m²
Surface fire line intensity	11 kW/m	10 kW/m	4 kW/m
Surface fire flame length	0.2 m	0.2 m	0.2 m
Surface reaction intensity	396 kW/m²	317 kW/m²	256 kW/m²
Surface fire spread distance/hr	8.3 m	9.1 m	5.1 m

4.2 Forest floor

4.2.1 Forest floor mass

The forest floor samples were collected from the different trial sites before the prescribed under canopy burn was implemented as well as within two weeks after the under canopy burn took place. The samples were thus collected from April 2019 – June 2019. Forest floor samples were collected and dried to determine the oven dry mass and litter depth measurements were also conducted on all trial sites.

Differences in fuel loading do occur between the different trial sites, more specifically between trial sites of different species, namely *Pinus patula* which recorded mean fuel loads of 40.5 tons ha $^{-1}$ and 57.4 tons ha $^{-1}$ on Berlin and Nelshoogte respectively and *Pinus elliottii where* fuel loads of 23.1 tons ha $^{-1}$ were recorded on the Blyde trial site. The trial sites showed a significant decrease in forest floor mass with repeated prescribed burning operations (Figure 4.1) and a post hoc test revealed which individual treatments differed significantly (Figure 4.2).

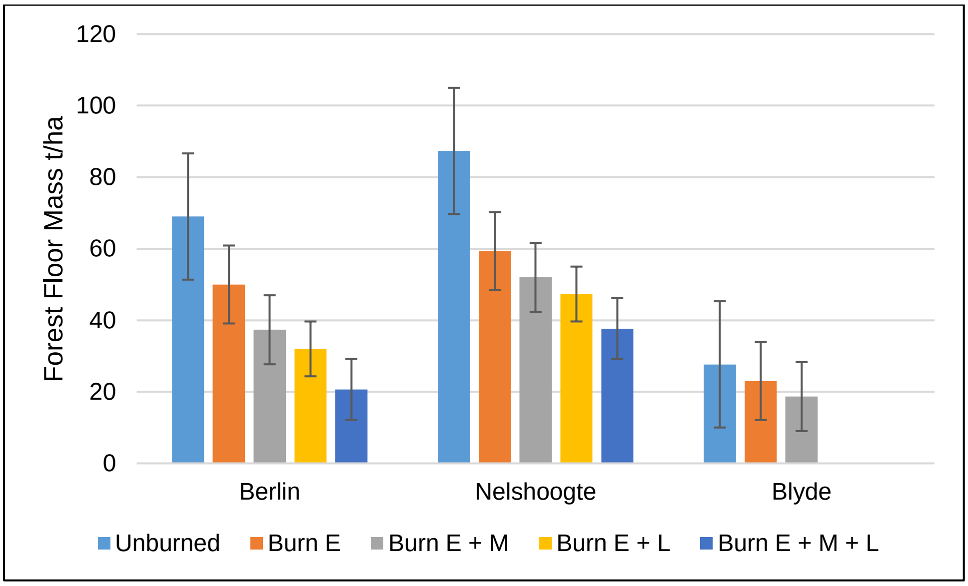


Figure 4.1: Impact of burning treatments on the forest floor mass (fuel load) on Berlin, Blyde and Nelshoogte plantation trial sites using prescribed fires during the Early (E), Middle (M) and /or Late (L) stages of the available burning window (refer Section 3.3.2.5).

Table 4.3 shows a significant difference in fuel load remaining among the burning treatments for the *P. patula* trials, and a post-hoc test revealed which individual treatments differed significantly (Figure 4.2). The fuel loads for various treatments in individual trial sites are shown in Figure 4.3.

Table 4.3: ANOVA test for burnt treatments in *P. patula* trials.

Effect	**SS**	**DF**	**MS**	**F**	**p**
Site	1673	1	1673	46.22	<0.0001
Rep	42	2	21	0.59	0.578
Burn tmt	8290	4	2073	57.28	<0.0001
Site*Rep	27	2	13	0.37	0.701
Site*Burn tmt	71	4	18	0.49	0.743
Rep*Burn tmt	313	8	39	1.08	0.457

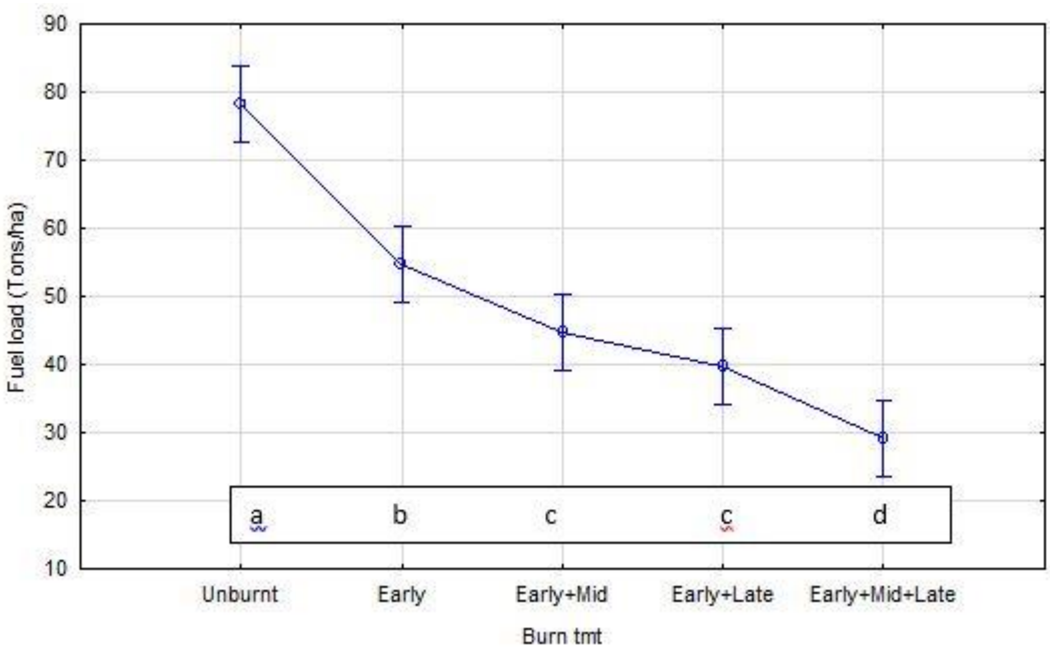


Figure 4.2: Combined analysis of *P. patula* trial sites with significance codes annotated.

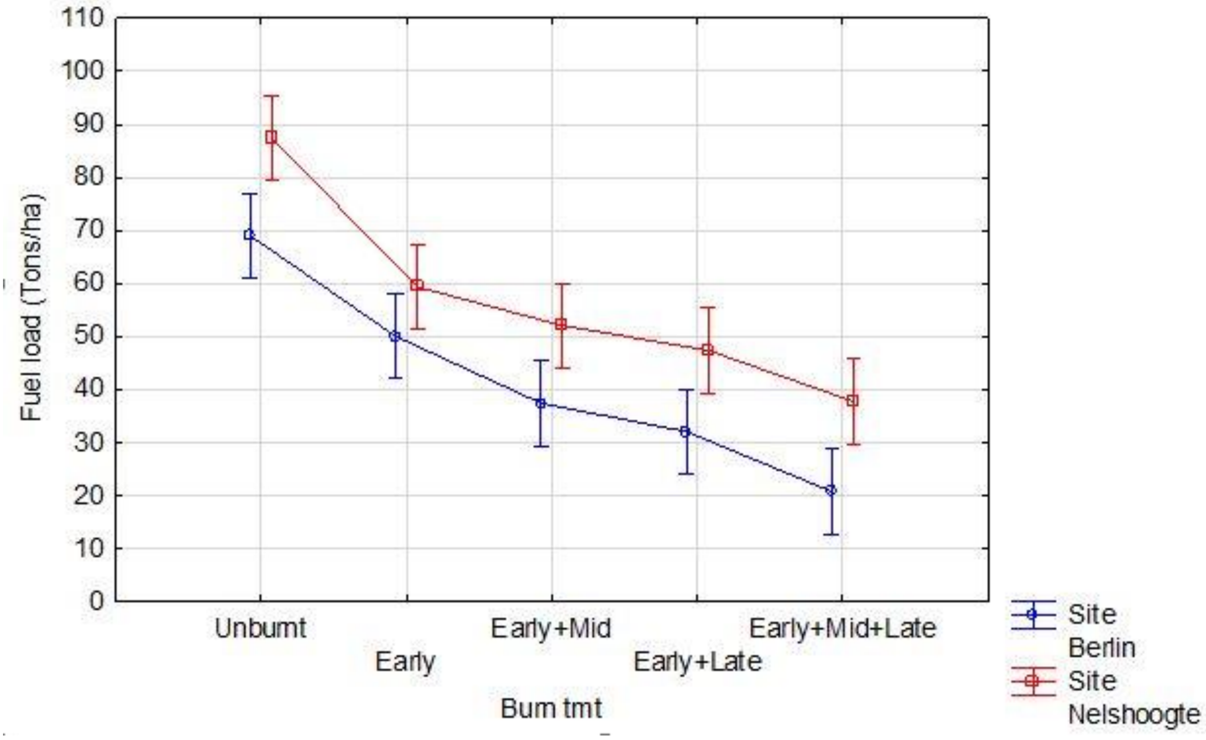


Figure 4.3: Impact of burning treatment on fuel load on the Berlin and Nelshoogte *P. Patula* sites.

Trial sites on Nelshoogte plantation showed a decrease in the forest floor mass from an average of 47 tons per ha in plots that had received two burning treatments down to 38 tons per hectare in plots that received three burning treatments. The average forest floor mass in the control plots was 87 t/ha, therefore an average difference of 49 tons per hectare of forest floor mass has been realised between plots that have never received under canopy burning treatments and plots that have received three burning treatments over a period of 13 years. Forest floor data was taken in 2019, thus representing the FF mass near rotation end for all combinations.

Trial sites on Berlin plantation showed a decrease in the forest floor mass from an average of 32 tons per ha in plots that had received two burning treatments down to 21 tons per hectare in plots that received three burning treatments (Figure 4.1) The average forest floor mass in the control plots is 69 tons/ha, therefore an average fuel load reduction of 48 tons per hectare of forest floor mass has been realised between plots that have never received under canopy burning treatments and plots that have received three burning treatments over a period of 6 years. It is interesting to note that the fuel load reduction achieved on Berlin and Nelshoogte is similar, namely a reduction of 48 tons/ha and 49 tons/ha respectively.

An ANOVA test for the Blyde site was conducted using Statistica statistical programme and the results are presented in Table 4.4.

Table 4.4: ANOVA test representing forest floor fuel load responses on Blyde site.

Effect	SS	DF	MS	F	p
Rep	18.8	2	9.41	3.54	0.130
Burn tmt	134.0	2	66.98	25.18	0.005

Table 4.5: Significant differences among burning treatments in the *P. elliottii* Blyde trial.

Burning Tmt combination	Fuel load (Tons/ha)	Significance code#
Early burn	28.11	A
Early+Mid	23.00	B
Early+Mid+Late	18.67	C

Treatments followed by the same letter code are not significantly different

Trial site on Blyde plantation showed a decrease in the forest floor mass from an average of 28.11 tons per ha in plots that had received one burning treatment down to 18.67 tons per hectare in plots that received three burning treatments (Figure 4.1), and the difference is significant (Table 4.4). An average difference of 9 tons per hectare of forest floor mass reduction has been realised between plots that have received one under canopy burning treatment and plots that have received three burning treatments. The numbers are significantly lower than the Berlin and Nelshoogte sites and this can be attributed to the difference in the forest floor characteristics (and hence the fire behaviour) between sites planted to different species.

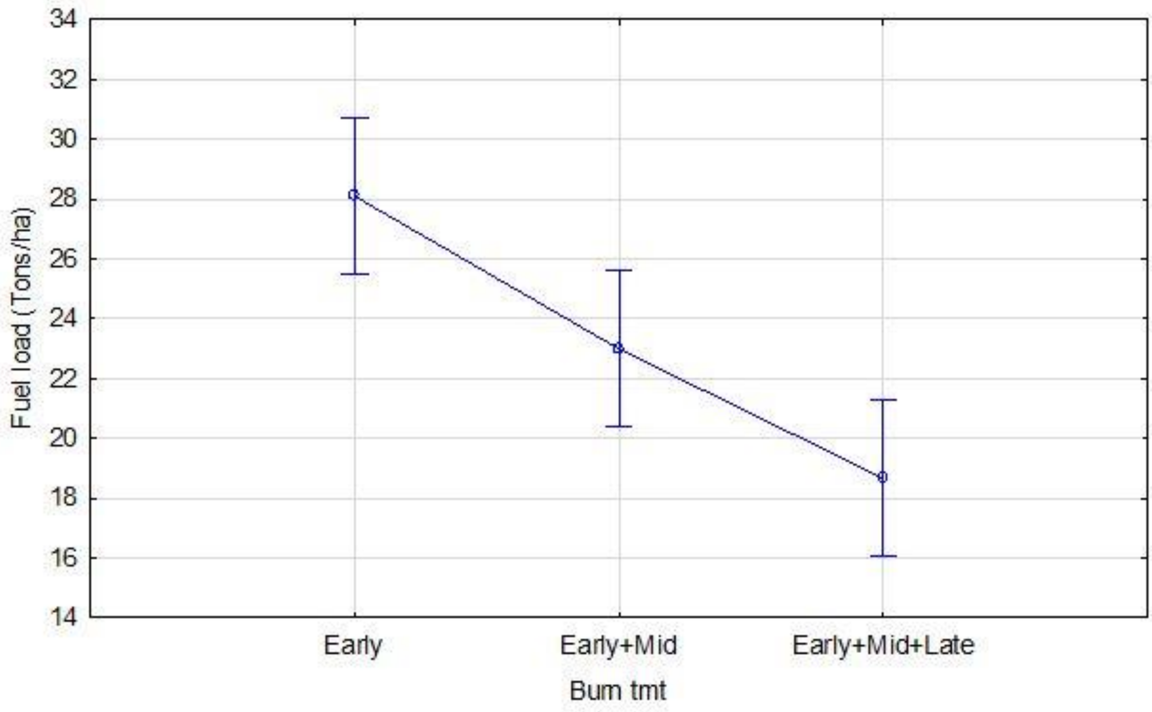


Figure 4.4: Effect of burning treatments on fuel load in *P.elliottii* trial site on Blyde.

A significant reduction in fuel load is observed in all three trial sites (Figure 4.1). The Berlin and Nelshoogte trial sites experienced a significant difference in fuel loads and Blyde being less marked however a reduction in fuel load is observed nonetheless. The Blyde trial site did not have any unburnt, control plots however the comparison between once burnt and three times burnt plots indicates a reduction in fuel load after repetitive under canopy prescribed burning operations.

4.3 Tree damage

For the purpose of this study the following aspects of tree damage were investigated, namely tree mortality, root damage and crown damage. The number of tree mortalities that occurred over the years were recorded in the various plots. The trial site plots where prescribed under canopy burning took place were investigated to determine if root damage occurred. Root damage primarily occurs when the fire intensity results in the fire burning down to the mineral soil, thereby exposing roots. These areas were quantified in relation to a specific root damage class (after Gresse, 2015). Damage to the crowns of the trees was identified by observing the degree of scorch to the crowns within the trial site plot. Crown damage is evident when the crowns or part of the crown exhibit the browning of needles. More subtle levels of damage could be gauged by monitoring needle fall in the months after the burning treatment implementation.

4.3.1 Tree mortality

The graphs in Figures 4.5, 4.6 and 4.7 provide some insight into the number of tree mortalities per plot which will have an impact on volume per plot, thus per hectare and PAI, measured in m^3 per hectare per year.

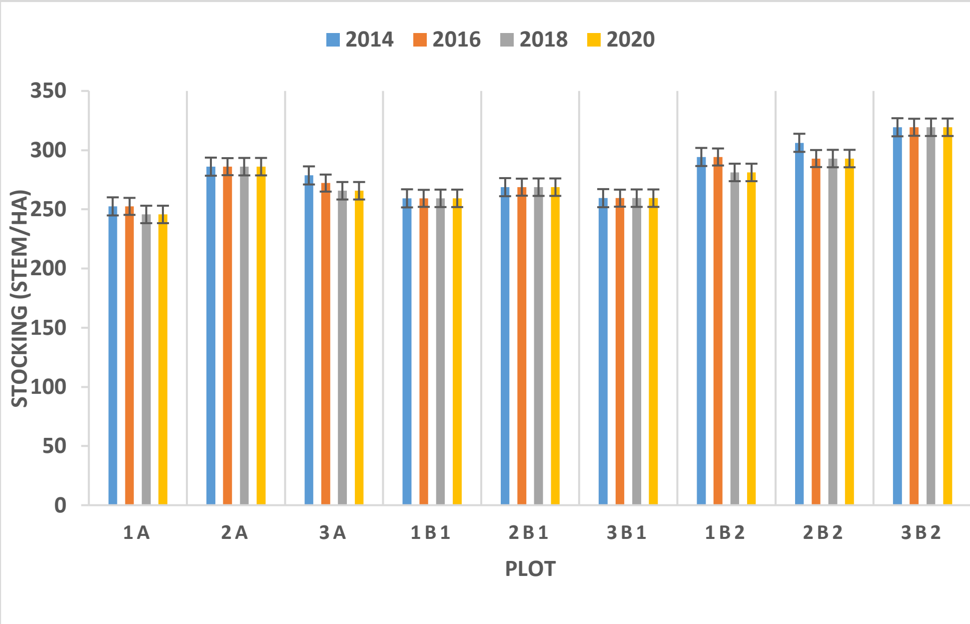


Figure 4.5: Nelshoogte – Changes in stocking from 2014 to 2020 among individual experimental plots in the Nelshoogte experiment (in stems per hectare).

It is noted that two trees within plot 1B2 died between 2016 and 2018 affecting the SPHA. This has an impact on the volume per hectare.

In plots 1A and 3A of Nelshoogte plantation (Figure 4.5) there were a total of three tree mortalities and this is noteworthy as these two plots were control plots that have never been burnt. In addition, mortalities occurred in plot 1B2 during 2017, two years after the burning treatment. It is concluded that tree mortality cannot only be attributed to the burnt plots as there is no correlation between number of burns and number of tree mortalities or the time of tree death.

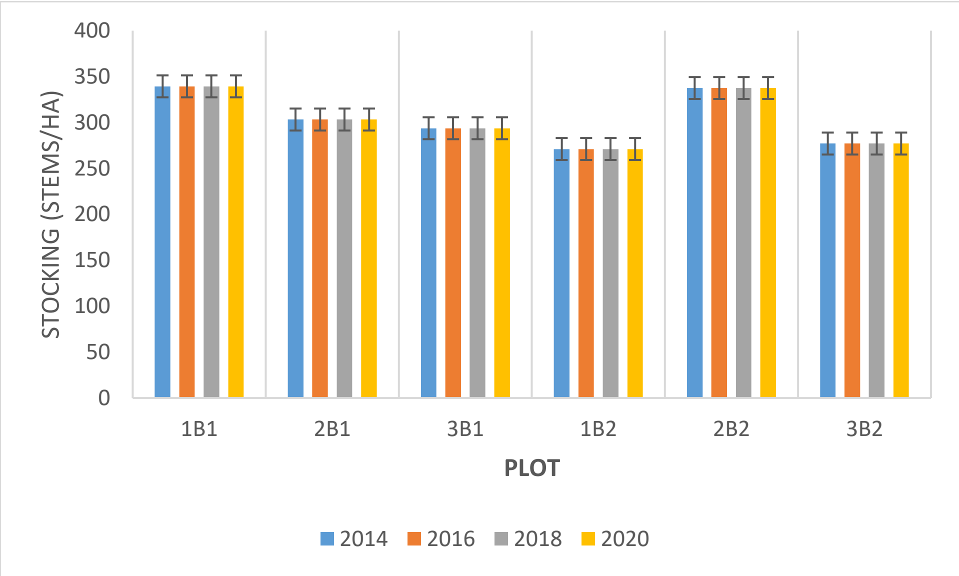


Figure 4.6: Blyde – Changes in stocking from 2014 to 2020 among individual experimental plots in the Blyde experiment (in stems per hectare).

Blyde:

No tree mortality occurred between 2014 and 2020 in any of the plots in A87 on Blyde plantation (Figure 4.6) Many factors can affect this however it must be noted that *Pinus elliottii* is known to be more resistant to fires when compared to *Pinus patula* (de Ronde, 1982).

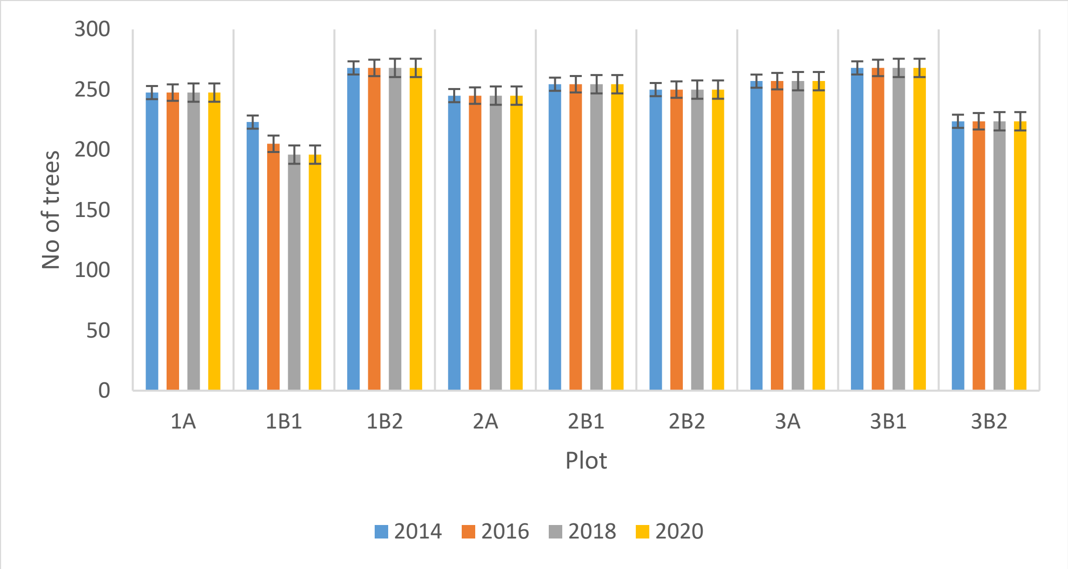


Figure 4.7: Berlin – Changes in stocking from 2014 to 2020 among individual experimental plots in the Berlin experiment (in stems per hectare).

Berlin:

Berlin plantation experienced three mortalities in plot 1B1 which was burnt twice, however zero mortalities in the plots that were burnt three times, and zero mortalities in the plots that received no burn. Furthermore, some tree mortalities occurred in 2017, several years after the second burn treatments were imposed (Figure 4.7). It is concluded that there is no correlation between tree mortality and number of burning operations on Berlin plantation. Seeing that the mortalities were clearly not related to the burning treatments, more realistic volume growth responses could be calculated by excluding trees that died between 2014 and 2020 from all volume and PAI calculations.

4.3.1.1 Relative density

The relative density was determined to ascertain whether the trees are facing intense competition which may lead to increasing mortality due to self-thinning towards the end of the rotation. The results are presented in Table 4.6.

Table 4.6: Relative densities of trial sites at time of implementation of third burns.

Plantation	Compartment	Status	SPHA	RD
Blyde	A87	Burn	312	5.60
Berlin	M31	Control	250	5.08
Berlin	M29	Burn	245	5.09
Nelshoogte	E38	Control	269	5.93
Nelshoogte	E28a	Burn	284	5.83

From Table 4.6 we can determine that the compartments are all in a healthy state of competition. All the compartments are in the zone of increasing competition (I.e. RD between 3 and 6) which is typical of commercial plantation forestry. The RD figures indicate that the trees are not under stress related to competition, or exposed to a lack of resources as a result of extreme competition.

4.3.2 Root damage

Minimal root damage occurred within the different trial site plots. The prescribed under canopy burning treatments were executed on days where the conditions were favourable for under canopy burning. Table 4.2 above indicates that the conditions on all three trial sites resulted in cool burns due to relatively high humidity, suitable temperatures and low wind speeds. Together with relatively high fuel moisture content particularly within the fermentation and humus layers resulted in a minimal degree of root damage.

The trial sites on Nelshoogte plantation did exhibit slightly higher degrees of root damage when compared to the Berlin and Blyde trial sites and this possibly due to the lower relative humidity and fuel moisture content on the day of the burn when compared to the Berlin and Blyde sites. Behave plus fire intensity modelling indicates that fire intensity was greatest on Nelshoogte plantation (Figure 4.9). Ten trees were selected per trial site plot that received prescribed under canopy burning treatments. A total of 60 trees were inspected per trial site and grouped according to the root damage classification system as per table 4.7, 4.8 and 4.9.

Table 4.7: Blyde - number of trees damaged per hectare per root damage class.

Blyde					
	Root damage class				
	0	1	2	3	4
No. of trees	188	64	14	9	0

Table 4.8: Berlin - number of trees damaged per hectare per root damage class.

Berlin					
	Root damage class				
	0	1	2	3	4
No. of trees	174	87	9	5	0

Table 4.9: Nelshoogte - Number of trees damaged per hectare per root damage class.

Nelshoogte					
	Root damage class				
	0	1	2	3	4
No. of trees	105	78	55	32	5

The average burning conditions on the day of the burn (Table 3.11) were used to draw a comparison between the degree of root damage and the burning conditions which affect the degree of fire intensity. Table 4.10 indicates the degree of root damage in relation to the average conditions on the day of the burn per trial site area.

The scores per root damage class indicate the number of roots damaged and the degree of root damage severity. Classes 0 and 1 indicates no root damage and less than 4 medium roots burnt through respectively. Class 2 indicates that 4 or more medium roots burned through, with Class 3 and 4 indicating more severe root damage.

Class 3 indicates 2 or more coarse roots burned through and Class 4 indicates 1 or more very coarse roots burned through.

Table 4.10: Comparison of root damage classification and burning conditions on the day of burn on all three trial sites.

Plantation		Blyde	Berlin	Nelshoogte
Root damage class	0	188	174	105
	1	644	87	78
	2	14	9	55
	3	9	5	32
	4	0	0	5
Burning conditions	AVG Temp (°C)	25.9	19.3	26.0
	AVG RH (%)	57.2	73.7	32.8
	AVG FMC (L) (%)	23.0	20.2	16.9
	AVG FMC (F&H) (%)	80.1	121.4	55.2
	AVG Fuel load t/ha	27.7	30.6	33.9

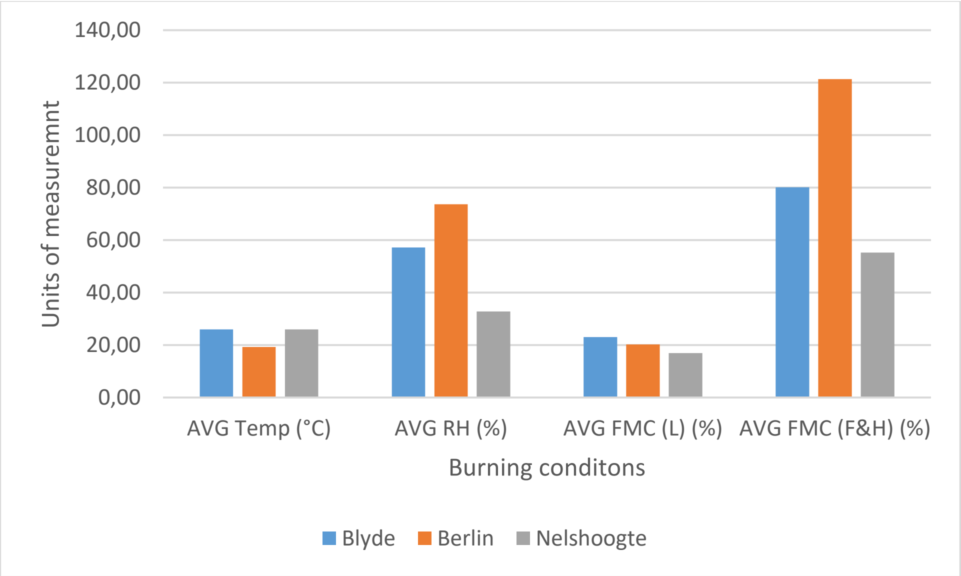


Figure 4.8: Burning conditions per plantation on the day of burn.

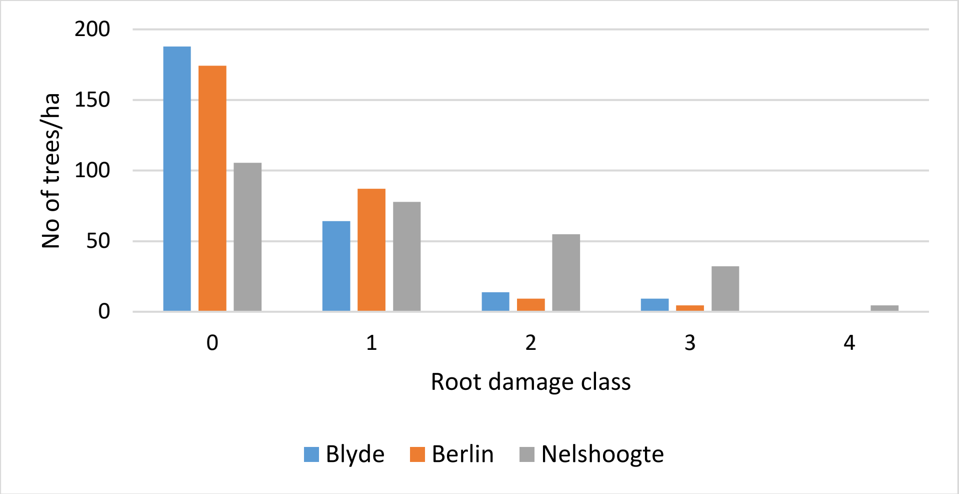


Figure 4.9: Number of trees damaged per hectare per root damage class.

4.3.3 Crown scorch and litterfall

Crown scorch was not evident in any of the plots on all three trial site areas. This can be attributed to low intensity burns and a resultant low flame height and slow rate of spread. The average flame height on all trial sites was below 25 cm and the average rate of spread was 0.001m/s for Blyde plantation and 0.005 m/s for Berlin and Nelshoogte plantation trial sites.

The litterfall measured is relatively consistent to previous studies (Gresse. 2015). The degree of litterfall between the control and the burn plot does not show significant variance. This can be attributed to the fact that the burns were conducted under the correct conditions and resulted in a cool, low intensity burn, therefore crown scorch was not evident. If crown scorch damaged trees in a way that was not evident from visual observations, it may have manifested as higher litterfall rates in burnt compartments and lower litterfall rates in the unburnt compartments in the month or two following treatment.

During the month of August 2019 on the Blyde trial site a weakly significant difference was noted between the control and burnt plot, however the other months do not show any significant differences, and this is attributed to the fact that no scorch took place, litter fall was therefore not impacted by the burning operation (Figure 4.10).

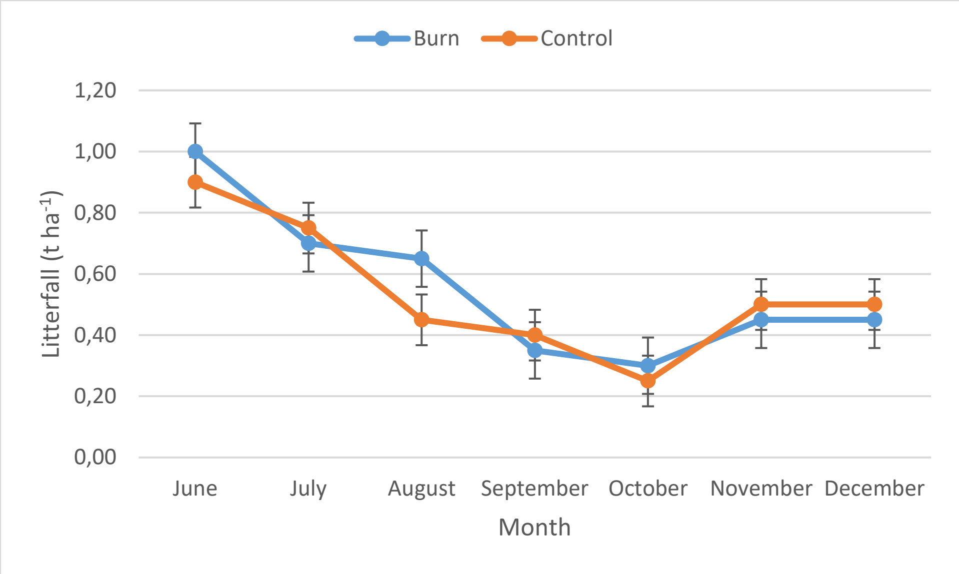


Figure 4.10: Blyde - Litterfall following the late-rotation under canopy fire of 2019.

Berlin plantation experienced no significant variation in litterfall rates between burnt and unburnt plots (Figure 4.11). Berlin plantation experienced a cool burn whereby the litter layer required manual manipulation (aeration) to encourage it to burn. (Refer to Figure 3.7) The RH on the day of the burn as well as the FMC was of such a nature that the burning could not take place until the litter layer was manually “lifted” and a strip ignition pattern used.

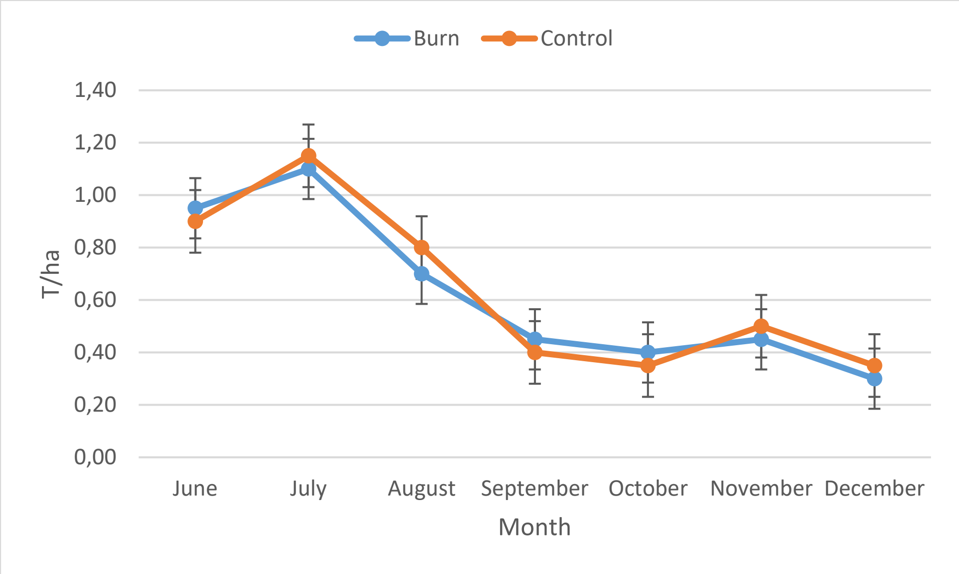


Figure 4.11: Berlin - Litterfall following the late-rotation under canopy fire of 2019.

Nelshoogte plantation does show significant differences among litterfall rates between burnt and unburnt plots during the months of June, July and August (Figure 4.12). Although no scorch was observed upon visual observation of the three plantations it must be noted that the burning conditions on Nelshoogte plantation allowed for a greater fire intensity, driven by a lower FMC and a lower RH on the day of the burn. Therefore it may be possible that a low degree of invisible needle damage did occur resulting in increased amount of litterfall from the burnt plots during the first 3 months following the burn.

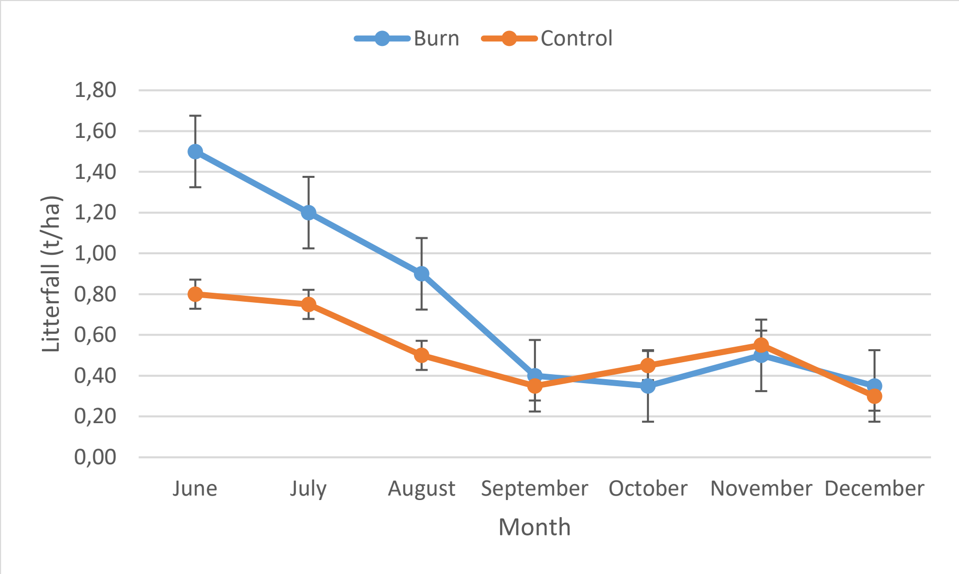


Figure 4.12: Nelshoogte – Litterfall following the late-rotation under canopy fire of 2019.

A seasonal trend is evident on all trial sites indicating that litter fall is greatest during the winter months of June, July and August. The litterfall rate decreases significantly during the spring and summer months from September to December. No data was collected during the months of January to May.

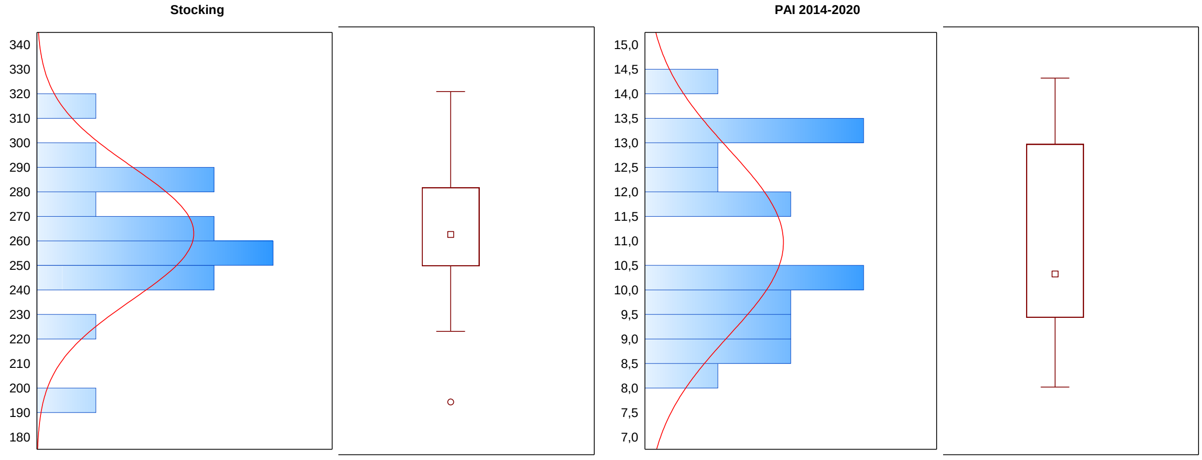
4.4 Growth responses

Table 4.11: Mean values for growth responses expressed as volume per hectare and PAI after final volume measurements 2020.

Plantation	Treatment	m3/ha	PAI
	Unburnt	231	8.7
	Twice burnt	257	9.58
Berlin	Three times burnt	304	11.7
	Once burnt	225	12.3
Blyde	Three times burnt	235	12.0
	Unburnt	397	13.5
	Twice burnt	331	12.4
Nelshoogte	Three times burnt	331	9.4

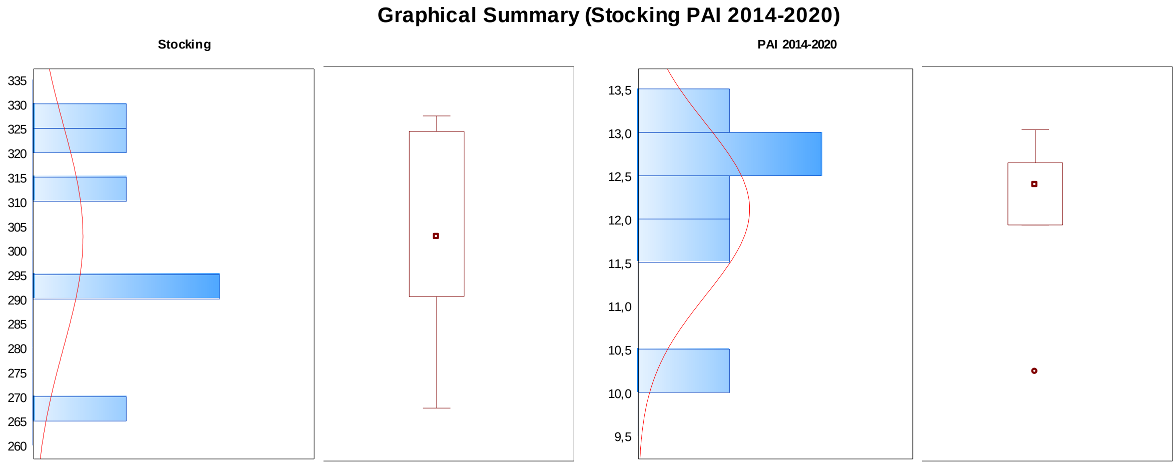
Descriptive statistics for the stocking and periodic annual volume increment (PAI) are shown in Figures 4.13 and 4.14. Figure 4.13 indicates a bell shaped curve that shows suitable distribution of data for analysis with ANOVA. The mean stocking is 263 SPHA which is in accordance with plantation compartment stocking of *Pinus patula* stands after receiving the final thinning in commercial plantations in South Africa (Charlton, 2018).

The descriptive statistics in Figure 4.14 indicate a slightly skew, bell shaped curve for both the stocking and growth statistics. The skewness values (-0.47 and -1.68), indicate that the distribution of the data sets are both still suitable for analysis ANOVA. The mean stocking in the *Pinus elliottii* site is 303 SPHA which is in line with stocking of mature Pine stands in commercial forestry plantations in South Africa. The mean PAI is 12.12 which is slightly above average considering that the trees in this study have reached an age whereby the growth may start to decline.



	Stocking	PAI 2014-2020
N:	18	18
Mean:	263	10,95
Median:	263	10,34
Min:	196	8,094
Max:	319	14,23
L-Qrt:	250	9,476
U-Qrt:	281	12,92
Variance:	730	3,572
SD:	27,03	1,890
Std.Err:	6,370	0,445
Skw:	-0,432	0,228
Kurt:	1,716	-1,288
95% Conf SD		
Lower:	20,28	1,418
Upper:	40,52	2,833
95% Conf Mean		
Lower:	249	10,01
Upper:	276	11,89

Figure 4.13: Descriptive statistics for stocking and PAI data for *Pinus patula* trial sites for Berlin and Nelshoogte plantations.



Stocking		PAI 2014-2020	
N:	6	N:	6
Mean:	303	Mean:	12,12
Median:	303	Median:	12,40
Min:	268	Min:	10,26
Max:	328	Max:	13,03
L-Qrt:	291	L-Qrt:	11,95
U-Qrt:	324	U-Qrt:	12,65
Variance:	514	Variance:	0,967
SD:	22,67	SD:	0,983
Std.Err:	9,254	Std.Err:	0,401
Skw:	-0,470	Skw:	-1,681
Kurt:	-0,803	Kurt:	3,213
95% Conf SD		95% Conf SD	
Lower:	14,15	Lower:	0,614
Upper:	55,60	Upper:	2,412
95% Conf Mean		95% Conf Mean	
Lower:	279	Lower:	11,08
Upper:	327	Upper:	13,15

Figure 4.14: Descriptive statistics for stocking and PAI for *Pinus elliottii* trial sites on Blyde plantation.

4.4.1 Analysis of variance results of periodic annual increment

An ANOVA test was conducted on stocking ad PAI values using the Statistica statistical programme and the results are presented in Tables 4.12, 4.13 below.

Table 4.12: ANOVA test analysing the impact of burning treatments on stocking of *Pinus patula* trial site plots situated on Berlin and Nelshoogte plantations.

	D. F.	SS	MS	F	*p*
Intercept	1	1241689	1241689	1287.223	<0.01
Burn_Treatment	2	1133	566	0.587	0.598
Site	1	3630	3630	3.763	0.124
Rep	2	693	347	0.359	0.719
Burn_Treatment*Site	2	1409	705	0.730	0.537
Burn_Treatment*Rep	4	1325	331	0.343	0.837
Site*Rep	2	368	184	0.190	0.834
Error	4	3859	965		
Total	17	12416			

Table 4.13: ANOVA test analysing the impact of burning treatments on growth (PAI) expressed as m^3 ha^{-1} a^{-1} on *Pinus patula* trial sites on Berlin and Nelshoogte plantations.

	DF	SS	MS	F	*p*
Intercept	1	2156.863	2156.863	3398.575	<0.0001
Burn_Treatment	2	0.691	0.345	0.544	0.6180
Site	1	15.876	15.876	25.016	<0.0071
Rep	2	1.642	0.821	1.294	0.3687
Burn_Treatment*Site	2	37.104	18.552	29.232	<0.0041
Burn_Treatment*Rep	4	2.490	0.622	0.981	0.5073
Site*Rep	2	0.379	0.190	0.299	0.7569
Error	4	2.539	0.635		

Burning treatments, site and replication did not have any significant effect on stocking (Table 4.12 and Figure 4.15). This allows for an evaluation of the PAI results without it being influenced by stocking differences. The analysis in Table 4.13 indicates that there is a highly significant interaction between the burning treatment and site ($p=0.0041$). This means that the effect of burning treatments on PAI was not constant, but differed from one site to the next, as can clearly be seen in Table 4.11 and Figure 4.16, specifically among the treatments that were subjected to three under canopy fires. Three burning treatments increased PAI at Berlin by a large margin (33.7%) but decreased it with a similar margin (28.7%) at Nelshoogte. This is the reason why burning as a main effect (i.e. across both sites) returns a non-significant result on PAI in Table 4.13 ($p=0.618$). The analysis further shows that the PAI is significantly different for site as a main effect ($p=0.0071$) (Table 4.13). The mean PAI for Nelshoogte (11.89 m^3 ha^{-1} yr^{-1}) can be considered an average value for late-rotation *P. patula* in South Africa while the PAI for Berlin (9.95 m^3 ha^{-1} yr^{-1}) is slightly below average**.** This difference was expected, because Gresse (2015) already reported differences in site quality among experimental sites: he calculated the Site index (base age 20) of the control plots at Berlin and Nelshoogte to be 23.1 and 24.9 respectively. It is concluded that the specific site had a large, significant impact on tree growth (PAI) and burning treatments had a variable impact.

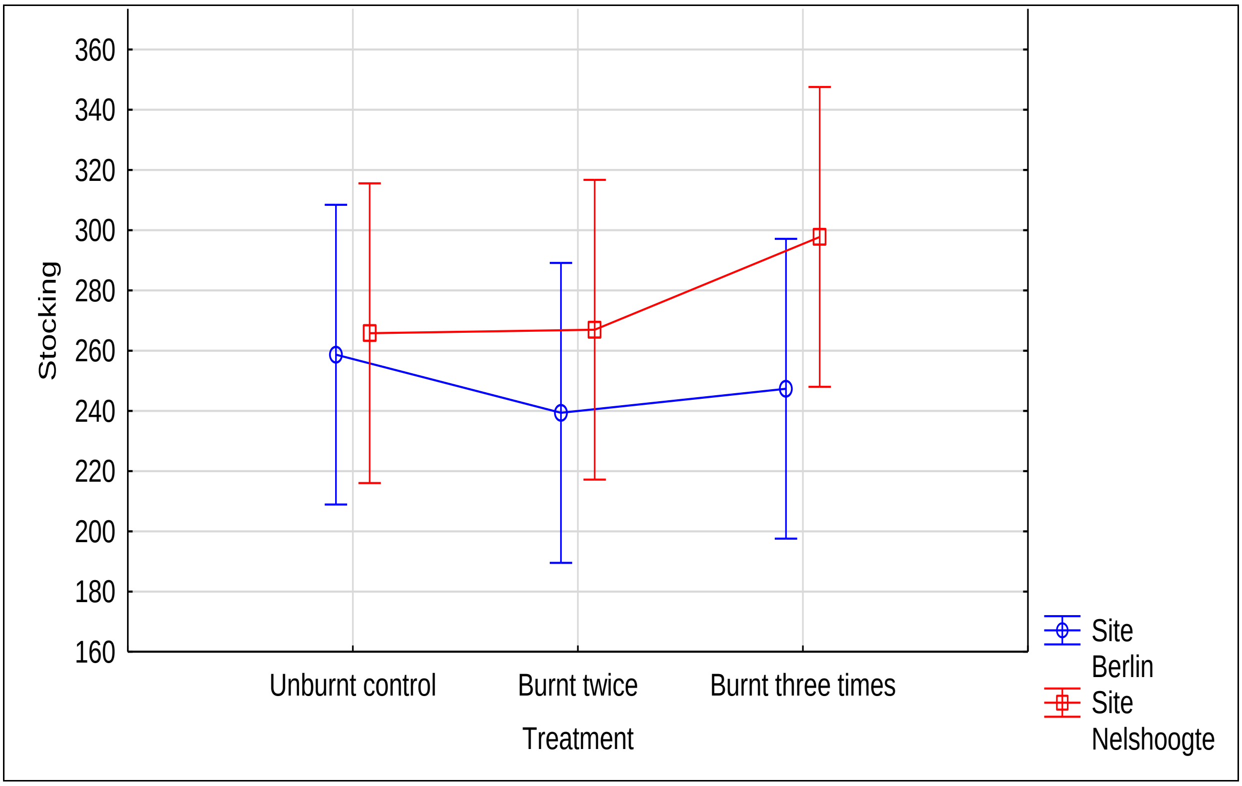


Figure 4.15: Stocking (SPHA) among treatments on *Pinus patula* trial sites on Berlin and Nelshoogte plantations.

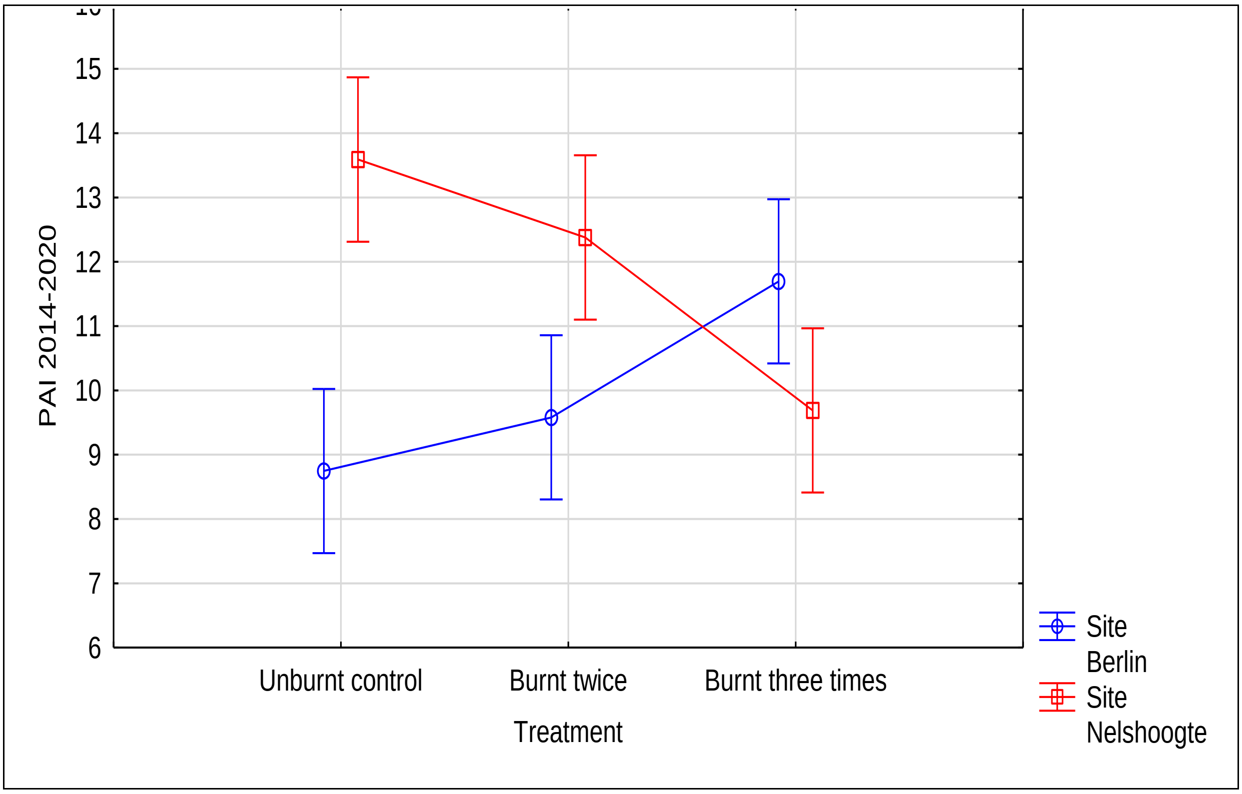


Figure 4.16: Effect of burning treatments on growth (PAI) expressed as (m^3 ha $^{-1}$ a $^{-1}$) on *Pinus patula* trial sites on Berlin and Nelshoogte plantations.

Table 4.14: ANOVA test analysing the impact of burning treatments on stocking of *Pinus elliottii* trial site plots situated on Blyde plantation.

	SS	Degr.of (Freedom)	MS	F	p
Intercept	880.6978	1	880.698	749.9092	<0.01
Burn_Treatment	0.1369	1	0.137	0.1166	0.750
Error	4.6976	4	1.174		

The impact of burning treatments on stocking in the Blyde trial was investigated and the results are shown in Table 4.14. Similar to the *Pinus patula* analysis, the analysis in Table 4.14 indicates that there is no significance among the burning treatments for stocking (Figure 4.17). This indicates that the growth rate of trees (measured as PAI) could be accurately compared as stocking was sufficiently similar, so as to not influence the results. It must be noted that no tree died on Blyde plantation as a result of the burning treatments (Figure 4.6).

Table 4.15: ANOVA test analysing the impact of burning treatments on growth (PAI) expressed as m^3 ha^{-1} a^{-1} on *Pinus elliottii* trial sites on Blyde plantation.

	SS	Degr. of (Freedom)	MS	F	p
Intercept	550451.018	1	550451.0	887.5	<0.001
Burn_Treatment	88.399	1	88.3	0.143	0.725
Error	2480.738	4	620.1		

The analysis in Table 4.15 and Figure 4.18 indicate that there is no significant effect of the burning treatment on growth expressed in PAI.

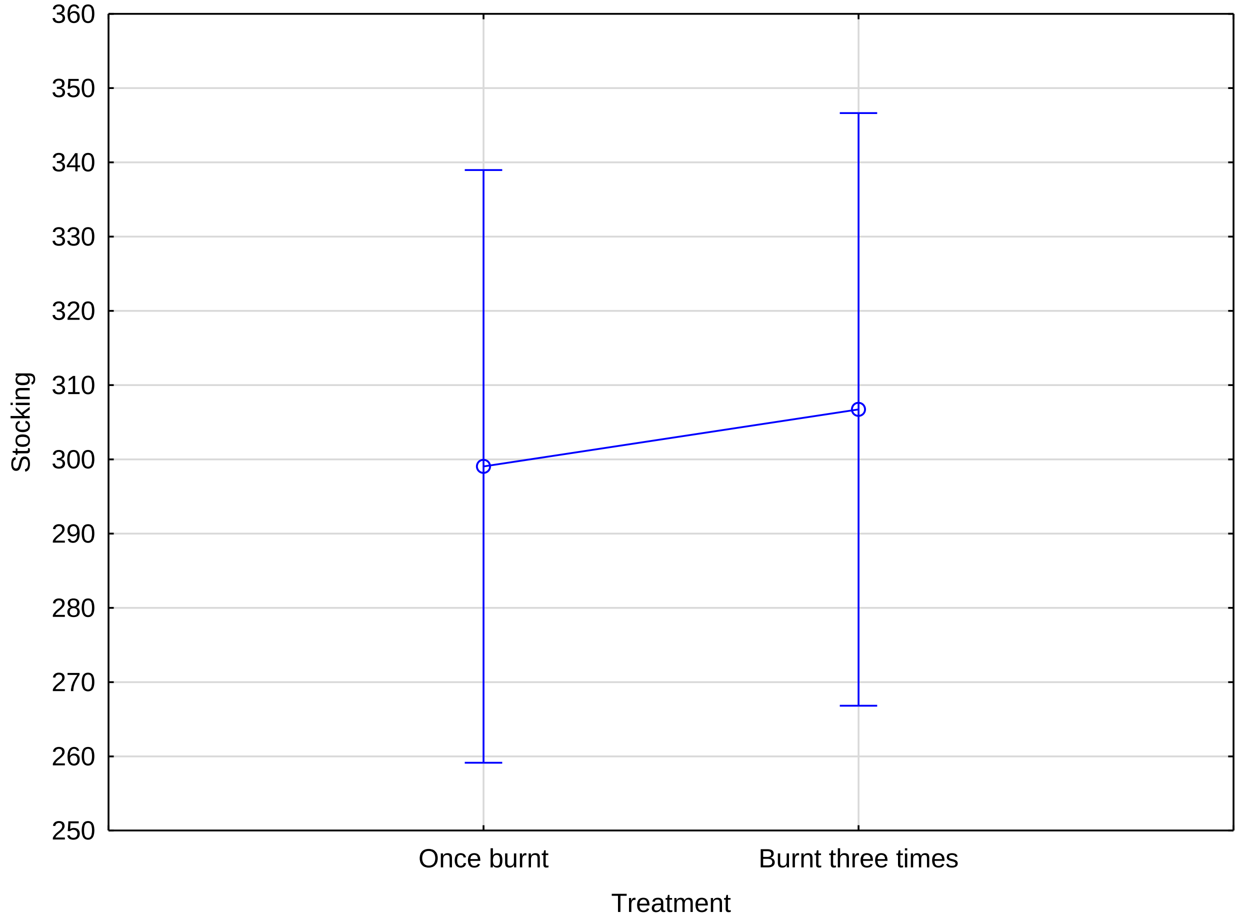


Figure 4.17: Stocking among treatments on *Pinus elliottii* trial sites on Blyde plantation.

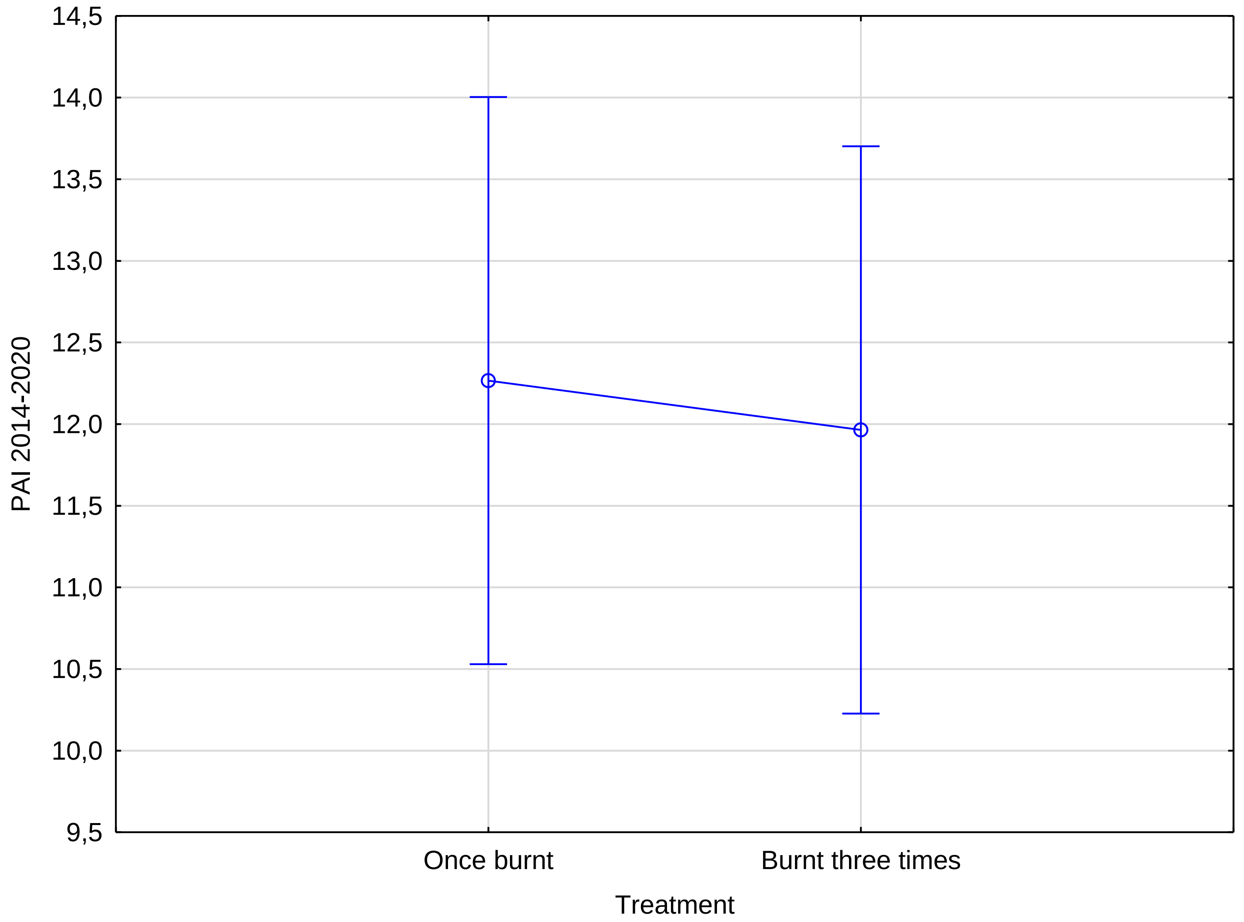


Figure 4.18: Effect of burning treatments on growth (PAI) expressed as $m^3\ ha^{-1}\ a^{-1}$ on *Pinus elliottii* trial sites on Blyde plantation.

5. Discussion

5.1 Burning conditions and fire intensity

From the data collected and infield observation of the different burning operations, the following recommendations can be made:

- The parameters to allow under canopy burning to take place can be revised
    - The allowable under canopy burning window is between the months from1 November to 31 March (SAFCOL, Intergrated Management System, 2018) It was found during this study that under canopy burning could only take place in *Pinus patula* stands in the dry winter season, in our case in the month of May, i.e. when the FMC of the fuel could sustain a fire.
    - It was found that during the month of May the RH of approx. 30% was suitable for *Pinus patula* to burn.

5.1.1 Fire intensity

The fire intensity was modelled using the Behave Pus 6 fire intensity modelling programme. It is noteworthy that the infield measurements correlate favourably with the Behave plus modelling output variables. Infield measurements such as flame height were measured to be below 25 cm on all trial sites on the day of the burn. Table 4.2 indicates the output variables from the modelling exercise and indicate a flame height of 0.2 m on all three trial sites.

The rate of spread was another variable that was measured infield. Table 4.2 indicates that the rate of spread was 0.1m/min for Nelshoogte and Blyde trial sites and 0.2 m/min for Berlin trial site. The infield measurements as depicted in Table 3.11 indicate that the rate of spread was measured to be 0.005m/s for Berlin and Nelshoogte trial sites and 0.001 m/s for the Blyde trial site. Converted back to m/min equates to 0.3 m/min for the Berlin and Nelshoogte sites and 0.06 m/min for the Blyde site. These figures from the infield measurements are thus similar to the modelled outputs from the Behave Plus fire intensity programme.

The accuracy of the model predictions for flame height and rate of spread would indicate that the fire intensity output variables such as the surface fire line intensity and the surface heat unit per area can probably also be accepted as a true reflection. Table 4.2 indicates that the modelled values for surface fire line intensity were highest on Nelshoogte plantation and lowest on Blyde plantation. The surface fire heat per unit per area was similarly greatest on Nelshoogte plantation and lowest on Blyde plantation. This is conducive to the fact that Nelshoogte trial site experienced the highest degree of root damage as well as the highest increase in litterfall soon after the burning operation.

A previous study by Bird & Scholes (2005) indicated that a moderate to low intensity fire of 140 kW/m in fuels with a fine fuel FMC of 10% would result in a flame length of 0.8 m and a rate of spread of 1 m/min. The Blyde trials therefore experienced a very low intensity fire which is supported by the rate of spread and flame length infield measurements as well as the Behave Plus modelled fire line intensity output data (Bird & Scholes, 2005).

In a simulation conducted to determine the efficacy of prescribed under canopy burning as a fixed defence mechanism to reduce the fire intensity of a wild fire, Van Wagtendonk (1996), found that the fire line intensity decreased from 491 kW/m^{-1} to 117 kW/m^{-1} when the fire entered the under canopy burnt area. Furthermore flame length decreased from 1.27m to 0.68m and the heat per unit area decreased from 14.63 kJ/m^2 to 4.02 kJ/m^2 (Van Wagtendonk, 1996).

5.2 Forest floor mass

The forest floor mass was reduced on all three trial sites after implementing the prescribed under canopy burn. An average reduction of 48 t ha^{-1} and 49 t ha^{-1} was achieved in the *Pinus patula* trial sites of Berlin and Nelshoogte respectively. An average reduction of 9 t ha^{-1} was achieved in the *Pinus elliottii* trial site of Blyde plantation.

During the burning operations it was noted that the *Pinus elliottii* trial site burnt more readily than the *Pinus patula* trial sites. This can be attributed to the different structure of the *Pinus elliottii* needles. Shorter, thicker needles result in increased aeration of the litter layer of the forest floor, providing more oxygen together with the higher resin content which increases flammability and fire intensity.

The needle structure and layering of *Pinus patula* needles result in a more compacted, less aerated layering of the forest floor in the Berlin and Nelshoogte trial sites. This results in a lesser degree of aeration and subsequent decreased amount of oxygen available during the burn. This was evident on Berlin and Nelshoogte plantation and the Berlin trial site required manual manipulation of the litter layer to allow for aeration and encourage the areas to burn as can be seen in Figure 3.6.

Numerous variables need to be considered when analysing the forest floor fuel loads after prescribed burning treatments. These variables include the conditions on the day of the burn and the subsequent intensity of the fire as this will have an impact on how much of the fuel load will be burnt. The species within the trial plots, as *Pinus patula* plots typically have a heavier fuel load when compared to *Pinus elliottii* plots as can be seen in Figure 4.3. Conditions within the trial plot also have an impact as the understory growth, slope within the plot, survival of trees within the plot and thus stocking all have an impact on the behaviour on the day of the burn. The fire behaviour affects the fire intensity and this has an impact on the forest floor fuel mass.

No significant fuel load reduction differences were observed on the Berlin and Nelshoogte sites, this could be attributed to the fact that the sites are of the same species, and they experience similar climate patterns, and have similar silvicultural management practices. The forest floor fuel mass on the Blyde site was considerably less than the Berlin and Nelshoogte site (Table 2).

The Nelshoogte and Berlin sites are within *Pinus patula* compartments and the Blyde trial site is within a *Pinus elliottii* compartment. It is expected that the forest floor mass in *Pinus patula* compartments will be greater than the forest floor mass in *Pinus elliottii* compartments due to the canopy density and *Pinus patula* having higher litterfall (Gresse C. , 2015) and a slower decomposition rate. The forest floor under *Pinus patula* is very dense and is known to accumulate at high stand densities and high altitudes, due to a reduced level of decomposition.

Ross and Du Toit (2004) state that commercial plantations of *Pinus patula* in Southern Africa can develop some of the heaviest FF fuel loads for this species in its established range. These heavy fuel loads accumulate under a cool climate and this is typical of the Berlin and Nelshoogte sites which are high altitude sites. This effect of FF fuel load accumulation is accumulative as stands are re-established over several rotations and if no fuel load reduction measures are in place, the fuel load increases. This results in a decline in stand productivity as the FF contains significant nutrient pools which are unavailable for growth or may be lost in the event of a wildfire (Ross & Du Toit, 2004).

The factors that lead to the FF fuel load accumulation are complex and consist of factors resulting in biomass (needle) production and factors affecting the rate of decomposition. Geochemical nutrient cycling are dominated by factors of biomass production and decomposition which are driven by inputs such as light, temperature, soil water, nutrient availability and carbon dioxide content of the atmosphere and decomposer organisms which result in decomposition and output of nutrients from the system. Accumulation occurs if there is an imbalance of ecosystem processes or if there is the absence of disturbances such as fire (Ross & Du Toit, 2004).

5.3 Tree damage

The different aspects of tree damage that were investigated include tree mortality, root damage and crown scorch.

5.3.1 Tree mortality

It is noted that no tree mortality occurred in the *Pinus elliottii* trial site, Figure 4.6. Tree mortality did occur in the *Pinus patula* trial sites, however it was shown that mortality occurred in the unburnt plots on Nelshoogte plantation. In Figure 4.5 it is evident that Nelshoogte plantation experienced tree mortality in two of the three control plots as well as two of the three plots that received three under canopy burning treatments. No tree mortality occurred in in the three plots that received two burning treatments.

Berlin plantation experienced tree mortality in one of the plots that received two under canopy burning treatments however no mortalities occurred in the control plots or the plots that received three under canopy burning treatments, Figure 4.7. Blyde plantation experienced no tree mortalities in the once burnt and three times burnt plots,

Figure 4.6. No control plots were available on the Blyde plantation experimental trial site.

It is evident that there is no correlation between under canopy burning treatments and tree mortality. It appears that either specific (unknown) stressors (probably from either localised competition or from biotic agents) may have acted on individual *P. patula* trees. These mortalities were scattered among several plots and treatments, resulting in low levels of mortality in these plots. The Blyde trial site consists of *Pinus elliottii,* known for being fire resistant and this was supported by the fact that no mortalities occurred within the *Pinus elliottii* trial site.

This is supported by a study conducted by de Ronde (1982) regarding the resistance of *Pinus elliottii* to fire damage. The study indicated that bark thickness is the most important factor relating to fire resistance. Bark thickness is strongly related to age and the older the tree the thicker the bark and therefore the more resistant the tree is to fire. Species such as *P.elliottii* are very resistant to fire and that tree mortality is highly unlikely when bark thickness exceeds 15mm. Bark thickness of 30 year old *Pinus elliottii* trees at 30 years of age was recorded to be between 20 and 25 mm and this would indicate minimal risk relating to cambium damage and tree mortality (de Ronde, 1982). The Blyde trial site also consisted of mature *Pinus elliottii* trees, indicating suitable bark thickness and together with low intensity burning operations could explain why no mortalities occurred.

5.3.2 Root damage

Root damage did not occur on a significant scale (Figure 4.10). On Blyde plantation 91.6% of the trees that were inspected experienced root damage in the 0 and 1 root damage classification zone which indicates that either zero or minor root damage occurred. A total of 8.3% of root damage occurred within the levels of 2 and 3 on the root classification system and no root damage was evident in the 4th level of the root damage classification system which would indicate severe root damage. Refer to Table 4.7.

On Berlin plantation 95% of the trees that were inspected experienced root damage in the 0 and 1 root damage classification zone. A total of 5% of root damage occurred within the levels of 2 and 3 on the root classification system and no root damage was evident in the 4th level of the root damage classification system, Table 4.8. The totals and the distribution of root damage scores in this *P. patula* stand was thus similar to that of *P. elliottii* at Blyde.

On the Nelshoogte plantation trial sites, 66.7 % of the inspected trees experienced root damage in the 0 and 1 level of the root damage classification system. 31.7% of the trees experienced root damage in levels 2 and 3 of the root damage classification system and 1.6% of the inspected trees experienced root damage in the 4th level of the root damage classification system, Table 4.9.

It is interesting to note in Table 4.1 that the burning conditions were suitable on all trial sites on the day of the burn, however Nelshoogte plantation prescribed burn took place on a day whereby the burning conditions resulted in a more intense fire when compared to the Blyde and Berlin trial sites. This is confirmed by the fire intensity modelling programme Behave Plus which indicates that the Nelshoogte prescribed burn resulted in the highest intensity fire which is confirmed in Table 4.2.

The RH on Nelshoogte was 32.8% and the FMC of the L and F&H layers was significantly lower than the Blyde and Berlin trial sites on their respective burn days. The average fuel load was higher on Nelshoogte plantation at an average of 33 tons ha $^{-1}$ and the air temp was warmer than the Berlin and Blyde sites at 26°C, Table 4.1. These climatic and site conditions on the day of the burn resulted in a hotter burn and this could explain why more of the inspected trees are classified in the 2 and 3 level as well as one tree being classified in level 4 of the root damage classification system (Table 4.9) as this resulted in a more intense fire.

It is evident that the Nelshoogte trial experienced a higher degree of root damage compared to the Blyde and Berlin trial sites. In a previous study conducted in 2015, 70% of root damage was recorded to be in the 0 - 1 root damage class with less than 10% of root damage occurring above class 2 in the root damage classification system. (Gresse C, 2015).

5.3.3 Crown scorch and litterfall

Tree scorch was not evident in any of the trial sites, therefore no impact of increased forest floor loading can be attributed to an increase in litter fall due to the prescribed burning treatment and crown scorch. The lack of crown scorch is due to the burning operations having taken place under favourable conditions resulting in low intensity fires and thus a cool burn.

Litterfall rates were within similar ranges found in previous studies. Previous studies have found litterfall rates in the Mpumalanga region of South Africa show that average annual litterfall rates of 5.89 t ha yr $^{-1}$ for *Pinus patula* (Dames, Scholes, & Straker, 1998) and 6.50 t ha yr $^{-1}$ for *Pinus elliottii* in the Western Cape area of South Africa (De Ronde et al., 1990).

No significant variation between the litterfall rates between the control and burnt plots were observed, due to an insignificant degree of crown scorch. The litterfall measurements took place from June 2019 to December 2019 on the three trial sites.

The highest monthly litterfall rate measurement on Blyde planation was 1 ton ha $^{-1}$, measured in June 2019, with 0.3 t/ha being the lowest amount of monthly litterfall measured in October 2019, Figure 4.11.

The *Pinus patula* site of Berlin plantation experienced 1.15 tons of litterfall in the month of July with 0.30 tons per hectare being the lowest measurement taken in December, Figure 4.12. Nelshoogte plantation experienced an increase in litterfall in the burnt plots following the burn when compared to the control plots. The highest measurement being 1.50 tons per hectare measured in June and 0.30 tons per ha measured in December, (Figure 4.13).

The increased levels of needle drop at Nelshoogte plantation continued for three months after burning (during the months of June, July and August) and then normalised and were in line with the litterfall measurements from the control plots. Although no visible crown scorch was evident and browning of the lower branches of the canopy occurred, it is possible that the increase in litterfall is due to the conditions on the day of the burn being more favourable for a hotter burn, resulting in a greater fire intensity and an increase in litterfall. This is confirmed with the output data from the Behave Plus fire intensity modelling programme which indicates that Nelshoogte plantation trial site experienced a prescribed burn with the highest fire intensity, (Table 4.2).

A research trial conducted in a *Pinus elliottii* stand in Lottering in the Western Cape experienced severe crown scorch resulting up to 3.7 t/ha of needle fall recorded within 30 days after the fire. This increased amount of litterfall cancels out the aim of under canopy burning which is fuel load reduction and therefore fire protection. Crown scorch should always be avoided and this highlights the importance of correct burning conditions and the impact of fire intensity (de Ronde, 1983).

5.4 Growth responses

Berlin plantation experienced an increase in PAI over the course of the three burning treatments, although there was a decrease in PAI experienced between the control and twice burnt plots. Blyde plantation trial site experienced a slight decrease in PAI when comparing the once burnt and three times burnt plots (Figure 4.18). It is noted that not one tree mortality was experienced in the Blyde trial site plots, indicating the suitability of *Pinus elliottii* for prescribed under canopy burning operations. Nelshoogte plantation trial site plots indicated sporadic changes in PAI in relation to the number of prescribed under canopy burning treatments. The Nelshoogte control, unburnt plots exhibiting a PAI of 13.5m^3 ha^{-1} a^{-1}, decreasing to 12.4m^3 ha^{-1} a^{-1} and decreasing to 9.40m^3 ha^{-1} a^{-1} in the twice burnt and three times burnt plots respectively.

It is noted that the control plots on Berlin plantation and Nelshoogte plantation exist in adjacent compartments to the plots where the prescribed under canopy burning operations took place. Although the compartments are adjacent to one another and in a similar geographical location, the control plots of the Nelshoogte trial site are 1 year older, planted in 1989 whereas the treatment plots were planted in 1990, however this fact is unlikely to influence the results.

The results indicate that fire intensity during the burn is of utmost importance. High intensity burns may likely result in increased crown scorch and root damage having a negative impact on growth (PAI). *P. elliottii* has a lighter fuel load and thus less smouldering of the F&H layers is likely to occur as occurs with *P. patula*. This will result in less likelihood of burning down to the mineral soil particularly around the base of the stem of the tree, and therefore less likelihood of root damage and negative impacts on growth (PAI).

While the litterfall was significantly greater in burnt plots of Nelshoogte following the fire, this effect had a short duration (Figure 4.13). It follows that the leaf area of trees would have been reduced slightly. However, being on the underside of the crown, it would not have had fairly small effect on light interception.

Previous research conducted in *Pinus pinaster* trial sites indicate that plots that received under canopy burning treatments and experienced serious crown scorch resulted in a negative effect in tree growth rate. Burned areas experienced an increase in diameter growth of 3 mm from 1978 – 1980 and 14,5 mm of diameter growth from 1978 to 1980 in unburned areas. This indicates a significant correlation between needle scorch and DBH (de Ronde, 1983)

In contrast, it appears that moderately high levels of damage to specifically the larger root size classes at Nelshoogte may have had a longer lasting effect, and that this may have primarily been responsible for the significant decrease in PAI following burning. The mortality in the larger root classes was a direct effect of smouldering litter layers around the tree base in some cases.

Future research should investigate methods to counter the smouldering effects sometimes observed in P. patula litter layers during controlled under-canopy burning.

It may be advisable for an inexperienced forester to first carry out under canopy burning treatments in *P. elliottii* stands. This is because it burns more favourably under a higher range of conditions, is resistant to fire, and the likelihood of negative impacts on growth (PAI) occurring due to the burning treatment is less then when compared to *P.patula* stands. The effects of under canopy burning on growth (PAI) in *P. patula* stands in this study was not consistent. One trial site showed an increase in PAI and one trial site showed a decrease in PAI. This can be site related but also affected by fire intensity and the resulting damage to the trees, which in turn would effect PAI.

6. Conclusions

6.1 Burning conditions and fire intensity

The prescribed under canopy burning treatments on all three experimental sites can be considered to be of a low intensity. The burning conditions on the days of the burns resulted in very low fire intensities. This is primarily due to the high fuel moisture content and high relative humidity on the day of each burn. Berlin plantation prescribed burn took place in May however due to the nature of the *Pinus patula* needle morphology and the compacted nature of the L layer the experimental plot struggled to burn until the L layer was manually manipulated to allow aeration, resulting in increased amount of oxygen and subsequently a successful burn.

Nelshoogte plantation experienced a burn of the highest intensity due to the lower relative humidity on the day and the lower fuel moisture content. Nelshoogte also recorded higher mortality in the thicker root classes, apparently due to a smouldering effect the sporadically persist at the base of some trees. This phenomenon was also observed by Gresse (2015) during the mid-rotation burning events. Blyde plantation experienced a very low intensity burn although it was in *Pinus elliottii* which is known to burn more readily than *Pinus patula*. The Blyde experimental trial site was burnt earlier then the two *Pinus patula* sites in April compared to May and the RH and FMC was high on the day of the burn, nevertheless the L layer was able to burn without aeration of the layer.

Infield measurements of rate of spread and flame height were similar to predicted outputs from the Behave plus 6 fire intensity modelling programme.

6.2 Forest floor mass

A clear reduction in forest floor mass was evident in all three experimental trial sites. The *Pinus elliottii* trial site on Blyde plantation experienced a reduction of the forest floor mass of 32% when comparing plots that received 1 burn with plots that received three burning treatments. The *Pinus Patula* trial site on Nelshoogte and Berlin plantations experienced a forest floor mass reduction of 19% and 34% when comparing plots that received two and three burning treatments for Nelshoogte and Berlin respectively.

The same trial sites experienced a forest floor mass reduction of 69% and 56% when comparing the control plots to the plots that received repeated prescribed under canopy burning treatments on Nelshoogte and Berlin respectively. These reductions in the forest floor mass are significant and prescribed under canopy burning is an effective management tool to be used to reduce forest floor mass and manage forest floor mass.

6.3 Tree damage

Tree mortality, root damage and crown scorch/litter fall were observed during the study. Tree mortality could not be correlated to the prescribed under canopy burning treatments. Tree mortality occurred in the control plots of the Nelshoogte site where no burning treatments took place. No tree mortality occurred on Blyde plantation whereby certain plots received three burning treatments. This is conducive to the fact the *Pinus elliottii* is known to be fire resistant. Tree mortalities did occur in burnt plots on Berlin and Nelshoogte plantation however the mortalities were sporadic and no correlation with mortalities and burning treatments could be established.

Root damage was observed on all three experimental trial sites, however due to the low intensity of the prescribed under canopy burning treatments many trees did not experience any root damage. The majority of the observed root damage occurred in class 1 and 2 of the root classification system which is the medium size root class. Minimal root damage was observed among the coarse root classes of many trees, however, where it did occur, it appears to have had a pronounced effect on the growth rate, as shown by the PAI decrease at Nelshoogte.

No crown scorch was observed in the three trial sites. This is due to low fire intensities and low flame height. Although no visible crown scorch was evident an increase in litter fall was evident after burning in the Nelshoogte trial site. Nelshoogte is the plantation that experienced the burning treatment of highest intensity and therefore resulted in an increased litter fall directly after the burn. The under canopy burning treatments had no effect on litter fall rates in the *Pinus elliottii* trial site of Blyde and the

Pinus patula trial site on Berlin plantation. The litter fall rates observed on the three trial sites indicate that the litter fall peaks during the winter months.

6.4 Growth responses

Low intensity burns resulted in the treatments having no significant impact on growth. The low intensity burns did not result in significant root damage or crown scorch therefore the impact on growth could not be observed as a result of the burning treatment. The observed tree mortalities occurring sporadically in unburnt and burnt plots indicate that the specific site has a more significant impact on growth responses.

A greater degree of root damage was observed on Nelshoogte plantation whereby a decrease in PAI did occur. This is consistent with the higher fire intensity experienced on Nelshoogte plantation. Trial sites such as Berlin experienced an increase in PAI with the corresponding burning treatment as can be seen in Table 5.1. This could be attributed to an ash bed effect, whereby certain nutrients such as Phosphorous are more readily available for uptake by the trees. This can be attributed to the increased amount of base cations found in the ash (Fisher & Binkley, 2000). No significant difference could be observed on the Blyde plantation trial site whereas a decrease in PAI in relation to the number of burning treatments was observed on the Nelshoogte trial site.

The low intensity under canopy burns results in the reduction of forest floor mass particularly, the litter layer. This will result in a modest loss of nutrients however the fermentation layer and humus layer is not removed during under canopy burning if done correctly, under the correct conditions. The majority of the nutrients are found in the F&H layers which mostly remain intact (Gresse, 2015). During an uncontrolled wildfire many nutrients would be lost as the fire would be of a high intensity, uncontrolled and result in the removal of the F&H layer and the nutrients associated with these layers. This can happen due to oxidation during the burn or through erosion losses immediately following a high intensity fire that destroys the entire forest floor. This would have a greater effect on growth when compared to the controlled fuel reduction burns.

7. Recommendations

The objective of the study was to determine the suitability of prescribed under canopy burning operations as a method to safely reduce forest floor fuel loads and the impact of this operation on the tree stand health and sustainability thereof.

From the results obtained in the study, it is evident that prescribed under canopy burning treatments can be successfully implemented as a management tool to safely reduce forest floor fuel loads in mature *Pinus elliottii* and *Pinus patula* stands in Mpumalanga, South Africa. If implemented correctly the desired results can be achieved without significant negative impacts on the trees being observed.

This study took place on three trial sites and a total of 24 replications (trial site plots) were included in the study. It would be ideal to conduct such a study making use of more trial replications and over a longer period of time. A longer term study, making use of more replications will assist particularly with the growth observations as many variables affect growth.

Further research is proposed to determine the impact of fuel moisture content and the impact of weather conditions on fuel moisture content on the L layer and the combined F&H layers. This will provide the basis for a modelling tool to allow users to determine fuel moisture contents based on prior and current weather conditions. This will give an indication as to the expected fire intensity on the day of the burn and guide users to ensure that the F&H layers are not affected during the burn.

The *Pinus patula* trial sites experienced difficulty when conducting the burning treatment. It is recommended that under canopy burning parameters are prescribed individually per species (or for groups of species) as the conditions required to enable a successful burning treatment differ between *Pinus patula* and *Pinus elliottii* species. *Pinus patula* requires a lower RH and a lower fuel moisture content to allow for a suitable burn when compared to *Pinus elliottii.*

Long term research is required to determine the sustainability of under canopy burning as a fuel reduction management tool. Research is required to determine long term impacts of tree growth, stand sustainability and environmental impacts such as greenhouse gas emissions.

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